(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 655 138 B1

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention of the grant of the patent:
29.04.1998 Bulletin 1998/18

(21) Application number: **93918034.5**

(22) Date of filing: **16.08.1993**

(51) Int Cl.[6]: **G01S 3/14**, A61B 5/06

(86) International application number:
PCT/GB93/01736

(87) International publication number:
WO 94/04938 (03.03.1994 Gazette 1994/06)

(54) **POSITION LOCATION SYSTEM**

ORTUNGSSYSTEM

DISPOSITIF DE LOCALISATION D'UNE POSITION

(84) Designated Contracting States:
CH DE ES FR GB IT LI NL

(30) Priority: **14.08.1992 EP 92307492**
27.01.1993 GB 9301569

(43) Date of publication of application:
31.05.1995 Bulletin 1995/22

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EP 0 655 138 B1

Printed by Jouve, 75001 PARIS (FR)

Description

Field of the Invention

The present invention relates to methods of and apparatus for, determining the location of an object and in particular, but not exclusively to methods and apparatus which employ a magnetic field which is sensed at the object.

Background of the Invention

It has been long appreciated that if the magnetic field around a field generating element, for example a generating coil, can be accurately mapped then it might be possible to determine the location of a field sensor, for example a sensing coil, relative to the generating coil, from the signals sensed by such a sensing coil. However, a problem associated with doing this is that there are in general many locations and/or orientations of the sensing coil within the field of the generating coil that will provide the same characteristic sensing signals in the sensing coil. In order to use a magnetic field for this purpose, additional information must therefore be provided.

Prior art approaches to providing the additional information required comprise either moving the generating and sensing coils relative to each other, or scanning the axis of the generated field past the sensing coil.

An example of the first approach is taught in US 3,644,825 wherein a system is disclosed for locating the position of a field sensor, comprising two orthogonal sensing coils, relative to a field generating element which relies on having knowledge of the direction of motion of the sensor relative to the generator. It should be noted that this system cannot detect the location of an object unless there is such relative motion, and its direction is known.

The second approach of scanning the axis of the generated field is disclosed, for position location in two dimensions, in US 3,121,228 and for position location in three dimensions in US 3,868,565.

US 3,121,228 describes how the distance and direction of a sensor, again comprising two orthogonal sensing coils, relative to a field generator, also comprising two orthogonal coils, can be determined. The two orthogonal generating coils are driven in phase quadrature so that the axis of the resultant field is caused to rotate within a plane. If the sensor is located within this plane then the axis of the field is guaranteed to scan past the sensor, and, because at any given distance from a field generator the field strength will be a maximum at the field axis, the sensor will detect a maximum in field strength at this time. The voltage induced in any one of the two coils forming the sensor will be dependent on the orientation of the coil relative to the field generator, and it is for this reason that in '228 two orthogonal coils are utilised in the sensor. The sum of these two voltages gives an indication of the distance between the sensor and generator, while the phase difference between the two voltages gives an indication of the direction of the generator relative to the sensor. It is thus essential to the operation of the location system of '228 that the axis of the field rotates and that two coils are present in the sensor.

In US 3, 868, 555 this approach of scanning the axis, or maximum intensity vector, of the field past the sensor is extended to allow location of the sensor in three dimensions. Whereas in two dimensions it is sufficient merely to rotate the axis of the field within the plane to be sensed to guarantee it passing through the sensor, in three dimensions the axis would have to be rotated so that it described the surface of a sphere in order to be certain it encountered the sensor. To ensure that the axis passed through all points on the surface of a sphere the motion of the axis would be such that it encountered the sensor only very infrequently, and thus measurements by the sensor of the maximum field strength would also be infrequent. To avoid this the location system of '565 drives the generator coils in a complex fashion so that the field axis tracks and rotates around the position of the sensor.

In order to locate the position of the sensor in three dimensions, according to the method of '565, three mutually orthogonal generating coils and three mutually orthogonal sensing coils are required and the three generating coils must be driven simultaneously by the three drive currents having amplitude and phase relationships between them which are controlled so as to direct the field axis towards the sensor.

The approach taken in '565 further requires that the various equations governing the voltage induced in a sensing coil located and orientated in a particular alternating magnetic field are solved dynamically in real time i.e. during the acquisition of data from the sensing coil. This requirement, in addition to limiting the speed at which the sensor can move while still being located successfully by the system, also means that should it be desired to locate more than one sensor, all apparatus will need to be duplicated for each additional sensor.

US 4,710,708 discloses a position location system, in which it is not necessary to scan the field axis. '708 employs multiple coil field generators and a single coil sensor, but utilises standard iterative algorithms to solve for all the variables of the relevant simultaneous equations, in a computationally intensive manner.

Summary of the Invention

According to a first aspect of the present invention there is provided a method of determining the location and/or

orientation of a field sensor relative to a plurality of field generators of known location, each field generator comprising a plurality of collocated field generating elements, each generating element being energized and a measurement being made at the field sensor of the respective field generated by the generating element, the method being characterised by the steps of:

1) for each field generator calculating, from the measurements of the field generated by each of its generating elements and an estimate of the orientation of the sensor, an estimate of the distance from that particular field generator to the sensor, and
2) utilising the estimates of distance from step 1), and the known location of the field generators to calculate an estimate of the location of the sensor;
3) employing the estimated location of the sensor from step 2) and the measurements of the field at the sensor to calculate a new estimate of the orientation of the sensor;
4) repeating steps 1) to 3) iteratively, with step 1) employing the new estimate of sensor orientation from the preceding step 3), to improve the estimates of location and orientation of the sensor.

The method of the first aspect of the present invention thus enables the location and orientation of a sensor to be determined without either relative motion between the sensor and the field generating element, or scanning of the axis of the field.

Furthermore, by calculating an estimate of the distance of the sensor from each field generator, a surprisingly accurate estimate of the position of the sensor is achieved in a computationally simple manner.

Since the method dissociates the stages of acquisition of data from the sensor, and processing of that data, rapid determination of the sensor location is facilitated. Furthermore the location of additional sensors may be determined simply by simultaneous measuring the field, generated by each generating element, at these other sensors and independently calculating their distances from the field generators. It should be noted that no modification of the field generating apparatus or method of driving the apparatus is required in order to determine the location of a plurality of sensors.

The applicants have discovered that advantageously the method of the first aspect of the present invention also allows the location of a sensor comprising a single sensing element, for example a sensing coil, to be determined, as will be explained subsequently. This is particularly advantageous for positioning applications in which two or more mutually orthogonal sensing coils, as required by prior art techniques, cannot be used.

According to a second aspect of the present invention there is provided a method of determining the location of a field sensor, comprising a plurality of collocated field sensing elements, relative to a field generator, comprising a plurality of collocated field generating elements, each field generating element being energized in turn and the value of the resultant field strength being measured at the field sensor, the measured field strength being dependent on the location of the sensor within the respective field, the method being characterised by the steps of:

1) calculating, by utilising all the values of measured field strength and an estimate of the direction of the sensor from the field generator, a direction dependent weighting factor for each field generating element so that the calculated field strength B is equal to the field strength B that would exist at the sensor if the axis of the field were directed towards the sensor,
2) iteratively altering the direction dependent weighting factors to maximise B and thus to determine to a desired level of accuracy the direction of the sensor from the field generator, and
3) employing the measured values of the field strength to calculate the distance of the sensor from the field generator and hence, from the direction of the sensor in step 2), the location of the sensor relative to the field generator.

This aspect of the invention thus provides a method of locating a sensor relative to a single field generator.

The invention further provides apparatus suitable for carrying out the methods of the first two aspects of the invention.

Preferred embodiments of the present invention will now be described, by way of example only, with reference to the accompanying figures in which:

Figure 1 shows a first embodiment of the invention,
Figure 2 shows the cartesian coordinate system employed for a sensor of arbitrary orientation located at point P,
Figure 3 shows schematically the resolution of the magnetic flux density at a sensor,
Figure 4 shows the coordinate system employed to locate a sensor relative to a field generator,
Figure 5 shows schematically a simulated circle of constant induced voltage, in a sensor, in two dimensions, which is employed in the first embodiment of the invention,
Figure 6 shows schematically three simulated spheres of constant induced voltage each centred on a field gen-

erator, which is employed in the first embodiment of the invention,
Figure 7 shows a flow chart of a first positioning algorithm used in the first embodiment of the invention,
Figure 8 shows the same schematic as Figure 6 when the location and orientation of the sensor have been determined,
Figures 9, 10 and 11 schematically show a coordinate system employed in a second positioning algorithm used in the first embodiment of the invention,
Figure 12 shows images of an endoscope obtained using the positioning system of the present invention on the left, and images obtained conventionally using X-rays on the right, (a) shows a sigmoid loop, (b) shows an alpha loop, and (c) shows a reverse alpha loop,
Figure 13 shows images of an endoscope within a patient obtained using the present positioning system on the left, and obtained using conventional X-ray imaging on the right, (a) shows an anterior view, and (b) shows a lateral view.
Figure 14 shows a second embodiment of the invention.

In a first embodiment the invention enables a sensor comprising a single sensing coil to be located in three dimensions relative to a plane defined by three field generators.

Detailed Description of the Drawings

With reference to Figure 1, three field generators 1 are mounted at known locations on a plane surface 2. Each field generator 1 comprises three electrically separate coils of wire (generating coils) 3 wound about a cuboid wooden former 4, which is approximately 40mm along one side. The three coils of each field generator are wound so that the axes of the coils are mutually perpendicular. The nine generating coils are separately electrically connected to an amplifier 5 which is able, under the direction of a controller 6, to drive each of the coils individually. Each coil comprises 40 turns of 0.45mm copper wire and has an inductance of approximately 75mH.

The sensor 7 comprises a single sensing coil of 200 turns of 42swg wire on a ferrite core of diameter 0.8mm, and length 12mm. Larger sensor coils will in general be more sensitive to the electro-magnetic fields generated by the generating coils, however the size of the coil is normally governed by the particular position location problem which is being addressed and frequently small sensor coils will be required. For an air-cored coil the sensitivity of the sensor depends on the area of the coil, however the sensitivity can be increased by utilising a high magnetic permeability material in the core, and in this case the sensitivity will depend more strongly on the length of the coil than on its diameter. The sensing coil is electrically connected to a measurement unit 8 which in turn is connected to the controller 6. The measurement unit 8 comprises an analogue to digital converter, and a matched filter (not shown).

In use, the controller 6 directs the amplifier 5 to drive each of the nine generating coils 3 sequentially. The amplifier 5 outputs a 10kHz drive signal of 3amps rms which causes the particular generating coil being driven to generate a quasi-static magnetic field. The frequency of the drive signal is chosen so that, within the range over which the location of the sensor is to be determined, the field generated is a near-field electro-magnetic field i.e the wavelength is long compared to the distance from the generating coil to the sensing coil.

Furthermore the drive signal frequency must be chosen so as to provide a compromise between sensor coil sensitivity, and the detrimental effects of electro-magnetic noise due to induced eddy currents within electrically conductive objects within the positioning range, since both of these aspects increase with frequency. In the absence of electrically conducting objects a frequency of several hundred kilohertz may be used giving good sensor sensitivity and thus good range and positioning accuracy. In the presence of highly conductive objects, this frequency may need to be reduced to a few hertz. In this case a sensor coil may no longer be appropriate and may be replaced by an alternative magnetic field sensor, such as a flux gate magnetometer. In this embodiment a drive frequency of 10 kHz has been found to be a suitable compromise between sensitivity and immunity to interference from electrically conductive objects.

Once the quasi-static field from a particular generating coil 3 is established, the value of the voltage induced in the sensing coil 7 by this field is measured by the measurement unit 8. The signal from the sensing coil 7 is first amplified and then sampled at 40 kHz by a 16 bit analogue-to-digital converter. The sampled signal is windowed using a Blackman-Harris window, the 10 kHz component is extracted by the matched filter and hence a value representing the voltage induced in the sensing coil 7 is established. This value is passed to the controller 6 which stores the value and then instructs the amplifier 5 to stop driving the present generating coil 3 and to start driving the next generating coil 3. When all nine generating coils 3 have been driven, or energised, and the corresponding nine voltages induced in the sensing coil 7 have been measured and stored, the controller 6 calculates the location and orientation of the sensor 7 relative to the field generators 1 and displays this on a display device 9. This calculation can be carried out while the subsequent set of nine measurements are being taken. Thus, by sequentially driving each of nine generating coils 3, arranged in three groups of three mutually orthogonal coils, the location and orientation of a single sensing coil 7 can be determined.

In order to describe the algorithm employed by the controller 6 to calculate the location and orientation of the sensor 7, a coordinate system will first be defined. In Figure 2 is shown a sensor, located at position P, whose axis is orientated along direction S. In general in order to determine the location and orientation of a single sensing coil within a field the x, y, z cartesian coordinates of the sensor and the elevation angle θ, and rotational angle ϕ, must be found (see Figure 2). The vector distance R of the sensor from the origin, O, of the coordinate system is also shown in Figure 2. Both the location and orientation of the sensing coil within the field will affect the voltage induced in the coil by the field, but rotation of the coil about its axis will not affect the induced voltage and thus does not constitute a further unknown quantity.

Assuming now that a single field generating coil 3 is placed at the origin O of the coordinate system with its axis directed along the z-axis. When the generating coil is energised a field will be produced at the sensor location P which has a magnetic flux density B. With reference to Figure 3 this magnetic flux B can be resolved along the three axes of the coordinate system to give Bx, By and Bz and subsequently resolved along the axis of the sensor thus:

$$B_{xy} = B_x \cos\phi + B_y \sin\phi \quad (1)$$

and

$$B_s = B_z \cos\theta + B_{xy} \sin\theta \quad (2)$$

The voltage V_s, induced in the sensor is related to the flux density via $V_s = k_s B_s$ where k_s is known and is a function of the frequency of the field and the characteristics of the sensing coil. It therefore follows from (1) and (2) that the voltage induced in the sensor at any x-y-z location and for any θ-ϕ orientation is given by,

$$V_s = k_s(B_z \cos\theta + \sin\theta(B_x \cos\phi + B_y \sin\phi)) \quad (3)$$

Formulae defining B_x, B_y and B_z are developed from standard near field electromagnetic theory in Appendix-A. Upon substituting the terms for B_x, B_y, B_z from equations (A-12) to (A-14) into (3), it can be shown that,

$$V_s = k_c k_s \left[\frac{(2z^2 - x^2 - y^2)\cos\theta + 3z \sin\theta(x\cos\phi + y\sin\phi)}{(x^2 + y^2 + z^2)^{5/2}} \right] \quad (4)$$

where k_c is known and is a function of the current through, diameter of, and number of turns on the generating coil. The five unknown quantities, x, y, z, θ and ϕ are evident in (4): all other variables are known.

Equation (4) has been derived, as stated above, for the case of a single generating coil 3 directed along the z-axis, there will of course be a corresponding equation for each of the three generating coils 3 of each of the three field generators 1.

It has been found that despite the complexity of this term (4) it is possible to determine the location and orientation of a single sensing coil by sequentially energising each generating coil. To explain this approach to position location the two dimensional case will first be considered.

Figure 4 shows a field generator comprising two orthogonal field generating coils D_x and D_y located at the origin of the coordinate system. The single sensing coil sensor is located at P and its axis is parallel to direction S. The angle a is the angle between vector direction R of the sensor from the origin, and the direction S of the sensor axis.

The voltages induced in the sensor when coils D_x and D_y are energised sequentially are respectively,

$$V_{sDx} = k_s(B_{RDx} \cos\alpha - B_{\theta Dx} \sin\alpha) \quad (5)$$

and

$$V_{sDy} = k_s(B_{RDy}\cos\alpha + B_{\theta Dy}\sin\alpha) \quad (6)$$

where the D_x and D_y sub-suffices relate to the field generated by the D_x and D_y coils. Upon substituting (A-1) and (A-2) from Appendix-A, (5) and (6) become,

$$V_{sDx} = \frac{k_c k_s}{R^3}(2\cos\theta\cos\alpha - \sin\theta\sin\alpha) \quad (7)$$

and

$$V_{sDy} = \frac{k_c k_s}{R^3}(2\sin\theta\cos\alpha + \cos\theta\sin\alpha) \quad (8)$$

It has been noticed that the value of $\sqrt{(V_{sDx}^2 + V_{sDy}^2)}$ remains constant for a constant value of α. From (7) and (8) we can write,

$$\sqrt{(V_{sDx}^2 + V_{sDy}^2)} = \frac{k_c k_s}{R^3}(4\cos^2\theta\cos^2\alpha + \sin^2\theta\sin^2\alpha - 4\sin\theta\sin\alpha\cos\theta\cos\alpha + 4\sin^2\theta\cos^2\alpha + \cos^2\theta\sin^2\alpha + 4\sin\theta\cos\alpha\cos\theta\sin\alpha)^{1/2} \quad (9)$$

which reduces to,

$$\sqrt{V_{sDx}^2 + V_{sDy}^2} = \frac{k_c k_s}{R^3}\sqrt{1 + 3\cos^2\alpha} \quad (10)$$

This can be thought of as corresponding physically to a circle of constant induced voltage in the sensor, centred on the field generator at the origin and lying in the x-y plane. This concept is shown schematically in Figure 5. If the two individual measurements of induced voltage V_{sDx} and V_{sDy} measured at the sensor are used to calculate $\sqrt{V_{sDx}^2 + V_{sDy}^2}$ a circular or rotating field of constant strength can be simulated since $\sqrt{V_{sDx}^2 + V_{sDy}^2}$ represents the maximum voltage that could be induced in the sensor if a rotating field were used. This is desirable since equation 10 gives a very simple relationship between R and α.

The extension of this analysis to three dimensions is readily performed mathematically and conceptually very powerful because the approach taken does not require the axis of the generated field to be steered towards the sensor, but simply requires sequential energising of the individual generating coils. Thus for position determination in three dimensions of a single coil sensor, assuming three mutually perpendicular generating coils located at the origin of the coordinate system, we have

$$\sqrt{V_{sDx}^2 + V_{sDy}^2 + V_{sDz}^2} = \frac{k_c k_s}{R^3}\sqrt{1 + 3\cos^2\alpha} \quad (11)$$

It should be noted that the term $\sqrt{1 + 3\cos^2\alpha}$ can only take values between 1 and 2, ignoring negative solutions and thus any value of R computed from (11) is only weakly dependent on the value of α. For example, if α is assumed to be $\pi/2$ whereas its correct value is zero, the value of R computed from (11) is 80% of its correct value. This in fact represents the worst case scenario since $\alpha=0$ means $\sqrt{1 + 3\cos^2\alpha} = 2$, while $\alpha=\pi/2$ means $\sqrt{1 + 3\cos^2\alpha} = 1$.

Hence for each of three field generators a bounded value for R, the vector distance of the sensor from that particular field generator, can be calculated without any knowledge of the orientation α of the sensor. Since there are three field

generators located at different known positions in the same plane (the x-y plane) and the distance R from each of them to the sensor has been calculated, the x-y-z coordinates of the sensor can be determined from simple trigonometry. This positioning methodology is shown schematically in Figure 6. The three simulated spheres of constant induced voltage centred on each of the three field generators, and bounded by the potential error in R, overlap at two regions. One region is above the plane of the field generators and the other is below. In most applications, one solution is clearly erroneous and the location of the sensor can easily be uniquely determined.

At this stage the location of the sensor (but not its orientation) has been calculated to a limited degree of accuracy. For some applications this may be adequate, but in general the precise location and probably orientation of the sensor are required. This is achieved by the use of an iterative procedure in which the estimate of the x-y-z coordinates of the sensor, derived from the values of R for each of the three field generators, are used in the appropriate equation (4) for each of the nine generating coils to estimate values of θ and ϕ for the sensor, from these α is calculated for each of the three generators. Although θ and ϕ could be calculated from only two versions of equation (4), all nine versions are employed to improve the rate of convergence of the solution and its immunity from noise. The three values of a can then be invoked in the appropriate equation (11) for each field generator to calculate an improved estimate for R for each of the generators. This process is repeated, progressively reducing the error in R and α for each generator until the desired level of accuracy is achieved. It should be noted that this technique avoids the problems of non-convergence which would arise if equation (4) were utilised directly because a good estimate for R has been found before equation (4) is employed, and the estimate for R is bounded as shown schematically in Figure 6.

In summary, and with reference to Figure 7, the algorithm utilised by the controller 6 is as follows:-

1. Assume α=0 initially. This ensures an over-estimate of R which guarantees an intersection of the radial distances from the three generator.
2. Measure the voltages induced in the sensor by each of the 9 individual generator coils, and then compute $\sqrt{V_{sDx}^2 + V_{sDy}^2 + V_{sDz}^2}$ for each of the three generators.
3. Invoke α in (11) and compute R for each of the three generators.
4. Compute the x-y-z coordinates of the sensor from the three values of R.
5. Invoke these coordinates in the appropriate version of equation (4) for each of the nine generating coils and compute an improved estimate of θ and ϕ. This can be achieved by the use of, for example, the Gauss-Newton Least Squares optimisation technique.
6. Use the improved estimates of θ and ϕ to calculate α for each generator.
7. Return to step 3 until the difference between the new and previous estimates of α reaches a sufficiently low value commensurate with the required positional accuracy in the x-y-z coordinates being achieved.

Figure 8 depicts schematically the three spheres of constant induced voltage when the errors in R have been reduced to allow the location of the sensor to be determined uniquely. The technique employed thus guarantees convergence to a unique location, with a precision that can be chosen in accordance with the requirements of the application. Indeed, it should be noted that in applications where the sensor is moving within the magnetic field, the number of iterations can be chosen dynamically for each calculation of the location of the sensor, thereby improving the efficiency of the process. For example, the first placement of the sensor typically requires 10 iterations before the solution is considered to have converged: this is considered to be so when the mean-square difference between the present and previous values of a is less than 10^{-6}. Even with rapid movements of the sensor, it is unlikely that its angle a will change markedly from one positional placement to the next. By using the final value of a arrived at during the first placement as the initial estimate in the second placement, the number of iterations required to achieve the same convergence is significantly reduced. And so on for all subsequent placements. Experiments have shown that as few as 3-5 iterations are required for convergence after the initial placement.

Although the algorithm described above with reference to Figure 7 ensures convergence to a unique location, allows both the location and orientation of a single coil sensor to be determined, and has proved to be robust even in the presence of noisy signals from the sensor coil 7, a second, alternative algorithm has been developed which has further advantages.

The first algorithm requires, at step 5, the solution of nine simultaneous equations relating θ and ϕ for each of the field generators to the estimate of the x, y and z coordinates of the sensor. This calculation can, dependent on the processing power of the controller 6, be time consuming, hence a second algorithm which is less computationally intensive has been developed. This algorithm enables the location and orientation of the sensor 7 to be determined more rapidly. The second algorithm is based on the realisation that mathematically the voltages induced in the sensor 7 by each set of three generating coils 3 comprising each generator can be treated as vector quantities. This mathematical treatment enables an angle ψ between the magnetic field lines and the direction vector of the sensor from a generator to be calculated. Once the values of ψ for each generator have been found there is no need to employ equation (4) since the values of α can be calculated directly from the values of ψ given a knowledge of the form of the

magnetic field. Since nine versions of equation (4) need no longer be solved this algorithm is computationally less intensive than the algorithm of Figure 7.

The second algorithm will now be described in greater detail. In order to explain the algorithm clearly and to demonstrate the mathematical insight on which it is based, the roles of the generating coils 3 and sensor coil 7 will be reversed i.e. for the purpose of the calculation the single axis field sensor 7 will be replaced by a continuously energised single axis field generating coil and the three orthogonal three-axis field generators will be replaced by three orthogonal three-axis field sensors. This is shown in Figure 9. Although it should be stressed that the reversal of roles here is simply for the purpose of mathematical elegance, this reversed configuration will in practice be feasible and in some position location applications may be desirable.

Referring now to Figure 9, let the vectors joining each three-axis sensor (10) to the single axis generator (11) be $\underline{R}_1$, $\underline{R}_2$ and $\underline{R}_3$ and let the angles between these vectors and the generator be α_1, α_2 and α_3. The field produced by the single axis generator (11) will pass through each three-axis sensor (10), and the magnitude and direction of the field may be determined by processing the signals produced by each of the three orthogonal sensor coils (12), forming each three-axis sensor (10), in response to the field. Let the signals in each of the three-axis sensor (10) be represented by the vector quantities $\underline{V}_1$, $\underline{V}_2$ and $\underline{V}_3$, where each component of the vectors corresponds to the signal in each of the orthogonal sensing coils (12). Let the angle between the field at each three-axis sensor (10) and the vectors $\underline{R}_1$, $\underline{R}_2$ and $\underline{R}_3$ be ψ_1, ψ_2 and ψ_3 respectively, as shown in Figure 10.

For the first estimate of the position of the generator 11, the orientation of the generator (11) is unknown, and α_1, α_2 and α_3 are assumed to be zero. The magnitude of the vectors $\underline{R}_1$, and $\underline{R}_2$ and $\underline{R}_3$ are then calculated from equation (11). As for the first algorithm, because of the nature of equation (11) a bounded value for the distance of the generator (11) from each of the three-axis sensors (10) is found and the overlap of these bounded values can be used to give an initial estimate of the x, y and z components of each of the vectors $\underline{R}_1$, $\underline{R}_2$ and $\underline{R}_3$.

The angles ψ_1, ψ_2 and ψ_3 are then calculated using the dot product, as follows:

$$\underline{V}_n \cdot \underline{R}_n = |\underline{V}_n| \, |\underline{R}_n| \cos\psi_n$$

$$\cos\psi_n = \frac{\underline{V}_n \cdot \underline{R}_n}{|\underline{V}_n| \, |\underline{R}_n|}$$

Having found ψ_n, we need to find α_n to improve the estimate of position. Referring to Figure 11 ψ is the known angle and α is the required angle. d represents the calculated distance from the generator to the sensor.

Since the generator is a simple dipole, the field at the sensor is given from equations (A-1) and (A-2) of the Appendix by:

$$B_d = \left(\frac{2k}{d^3}\right) \cos\alpha$$

$$B_\alpha = \left(\frac{k}{d^3}\right) \sin\alpha$$

The angle of the field at the sensor is given by:

$$\tan\psi = \frac{-B_\alpha}{B_d} = \frac{1}{2}\tan\alpha$$

and so α is obtained from ψ using:

$$\tan\alpha_n = -2\tan\psi_n$$

Having found a new estimate for α_n, a new estimate of the generator position is calculated using equation (11).

The process is repeated until the position converges to the required degree of accuracy.

Once the position of the generator (11) has been determined in terms of $\underline{R}_n$ and α_n the orientation of the generator may be calculated in terms of θ and ϕ as follows.

Let $\underline{U}$ be a unit vector defining the orientation of the generator relative to the sensors. Using the dot product, we can set up three equations to determine the three unknowns in $\underline{U}$.

$$\underline{R}_1 . \underline{U} = |\underline{R}_1| \, |\underline{U}| \cos\alpha_1 = |\underline{R}_1| \cos\alpha_1$$

$$\underline{R}_1 . \underline{U} = |\underline{R}_2| \, |\underline{U}| \cos\alpha_2 = |\underline{R}_2| \cos\alpha_2$$

$$\underline{R}_3 . \underline{U} = |\underline{R}_3| \, |\underline{U}| \cos\alpha_3 = |\underline{R}_3| \cos\alpha_3$$

These linear equations are solved to find $\underline{U}$, and then the orientation in terms of θ and ϕ is given by:

$$\theta = \arctan\left(\frac{\sqrt{U_x^2 + U_y^2}}{U_z}\right)$$

$$\phi = \arctan\left(\frac{U_x}{U_y}\right)$$

(note that a four quadrant arctan function should be used).

Although the formulation of the second algorithm has thus far been for the case of a single axis generator and multiple axis sensors the algorithm can be applied to the case of a single axis sensor and multiple axis generators. The only modification required between the two cases is the method by which the raw data for the algorithm (i.e. the voltages induced) is acquired. The equations developed above are directly applicable to the single axis sensor multiple axis generator case since the magnetic coupling between two coils is the same irrespective of which of the two coils is being driven.

The steps to be followed when employing the algorithm for the single axis sensor and multiple axis generator case will now be summarised: -

1. Sequentially energise each of the three generator coils in each of the three generators 1 and measure the voltage induced in the sensor coil 7 by each generator coil i.e. measure V_{1x}, V_{1y}, V_{1z}, V_{2x}, V_{2y}, V_{2z}, V_{3x}, V_{3y}, V_{3z}.
2. Invoke α_n in equation (11) and compute $|\underline{R}_n|$ for each of the generator 1, 2 and 3. (for initial estimate set α=0).
3. From the intersection of three spheres of radius $|\underline{R}_n|$ calculate the vector quantities $\underline{R}_1$, $\underline{R}_2$ and $\underline{R}_3$.
4. Taking the three voltages induced in the sensor coil 7 by a single generator 1 as a vector quantity e. g.

$$\underline{V}_1 = V_{1x}\,\underline{x} + V_{1y}\underline{y} + V_{1z}\,\underline{z}$$

calculate the angle of the field ψ_n from the dot product $\underline{V}_n . \underline{R}_n$.

5. Calculate the angles α_n between the vectors $\underline{R}_n$ and the sensor axis from ψ_n and equations A-1 and A-2.
6. Repeat steps 2 to 5 until the desired level of positioning accuracy has been achieved.
7. Use final values of α_n and $\underline{R}_n$ to calculate the orientation of the sensor coil in terms of θ and ϕ.

It has been found that use of the second algorithm can improve the speed with which the location and orientation

of a sensor is determined by a factor of approximately 15 compared to the first algorithm.

For both algorithms the location and orientation of more than one sensor can be determined without the need to replicate the field generators 1 and amplifier 5. The field generated by any one field generating coil is measured at each of the sensors and the location and orientation of the sensors are simultaneous and independently calculated. The positions of the sensors may of course all be displayed on a single display unit 9.

The simple, small sensor used in this embodiment means that it can provide position location in many situations where there is insufficient space for the three coil orthogonal sensor used in prior art position location systems. A particular field of application is the medical field, where access through body vessels is required, for example in endoscopy or non-invasive cardiovascular heart surgery. In these medical situations the present location system may replace the use of x-ray imaging (fluoroscopy), giving considerable advantages in cost and eliminating x-ray exposure to both patients and medical staff. The low frequency magnetic fields used by the present system render the human body transparent, while the use of low field strengths ensues the system is intrinsically safe.

During endoscopy it is desirable to know the path of the endoscope through the body. This may be achieved using the present location system in three ways. Firstly, the single sensing coil may be pulled along the biopsy tube and its position at regular intervals along the tube stored and displayed to provide a 3D map of the path. Secondly, a tube containing approximately a dozen single coil sensors may be placed in the biopsy tube of the endoscope and the location of each of the sensors determined. This would be a retro-fit to existing endoscopes. Alternatively, the single coil sensors may be placed in the wall of the endoscope during manufacture. In the second two cases a real time picture of the path of the endoscope would be available at all times to the endoscopist.

The present positioning system has been utilised in clinic field trials to image in three dimensions the total configuration of a colonoscope within the human abdomen. A sensor according to the present invention was placed inside the biopsy channel of an endoscope.

The small inner diameter of the biopsy channel, typically 3. 7mm for a colonoscope, not only dictates that the sensor be of vanishingly small diameter, but also that it may only comprise a single coil, typically 1cm in length, orientated along the axis of the instrument. The algorithms of the present positioning system processes the signals from this sensor in such a way as to calculate the position of the sensor within the biopsy channel independent of its orientation. Such independence is crucial in colonoscopy since the sensor may adopt any orientation for a single x-y-z location.

The positioning algorithm resides as software within an IBM 486 personal computer which, upon processing the information taken from the sensor at numerous discrete positions along the biopsy channel, then displays the path followed by the sensor as a continuous line on the monitor. Clearly this path corresponds precisely to that of the endoscope. Moreover, because the information from the sensor at each location relates to three dimensions, the imaged path on the monitor is likewise displayed in three dimensions. Visually the system achieves this by the use of "grey scale" colour coding whereby portions of the path further from the viewer (i. e. down into the screen) appear in darker shades of grey than the "under" portion. This feature is unique among all conventional imaging techniques for colonoscopy and represents a major advance in the field.

To display the path of the endoscope, the endoscopist first passes the sensor down the biopsy channel until it reaches the tip of the endoscope. For convenience we have encapsulated the sensor within a hollow tubular catheter of the type used routinely with endoscopes. The catheter is then withdrawn at a uniform speed (although this is not critical) while the system repeatedly determines the position of the sensor at discrete instances during its motion. During withdrawal the path of the instrument is displayed on the monitor in three dimensions. In many situations a total image of the endoscope is not required, in which case the sensor need only be withdrawn along that portion of the instrument of interest. To cater for patients lying in a variety of positions, perhaps changing during the investigation, the image may be rotated in any direction. This is particularly advantageous in establishing the radius of curvature of any bend in the endoscope that happens to lie along the viewing axis. For example, a bend that is in fact gradual, and hence poses no concern, can appear abrupt if viewed from some directions. A useful zoom facility on the image is also provided. When the system is in normal use, the system display would ideally be sited next to a standard camera monitor used to display the view from the endoscope. In this way the endoscopist is conveniently presented with the path of the instrument in three dimensions on one display, and the internal view from the endoscope optics on the other.

Initial validation of the system was performed with the aid of a rigid plastic framework to hold the endoscope in one of a number of predefined configurations. X-ray imaging and the present magnetic field system were applied to seven different configurations of the endoscope. These included a sigmoid loop, an alpha loop, a reverse alpha loop, a gamma loop, and an "N" loop. The results, three of which can be seen in Figure 12 showed close agreement between the image produced by the present positioning system (shown on the left) and the X-ray image (shown on the right) in each case. The nature of the overlapping portions of the colonoscope can be clearly seen from the images produced by the present positioning system. Some distortion of the images was caused by the metallic construction of the colonoscope perturbing the magnetic fields. However, this was minimal and the colonoscope configuration is clearly evident from the images.

The clinical trails involved three patients undergoing colonoscopy for a number of different indications. Ethical approval was obtained, as was written consent. The patients were sedated with a combination of pethidine and midazolam before the examination. The colonoscope used was a Pentax type FC38LH.

For the majority of each examination, the sensor was fully inserted into the biopsy channel, and the display was configured to show the progress of the tip of the endoscope in real time. When progress became difficult, the sensor was withdrawn, which immediately produced an image on the screen of the total path of the endoscope. With the aid of this image the removal of loops was straightforward, by using clockwise or anti-clockwise twist and simultaneous withdrawal of the endoscope. Similarly, when re-inserting the instrument the reformation of loops was prevented by a combination of abdominal pressure and torque. Where abdominal pressure was required the sensor was positioned in the loop, so enabling the endoscopist to see, by referring to the displayed image, whether pressure was being applied in the desired direction and to the correct extent. In each case examination around to the caecum was achieved (i.e. total colonoscopy) and the procedure was tolerated well by the patients. During the examinations, X-ray pictures were taken for comparison against those obtained with the magnetic system. Two of these, a plan and side view, are shown in Figure 13 together with the corresponding image from the magnetic system. Agreement between the two is very close, the deviation being largely attributable to patient movement between the two exposures.

The system has been shown to image the configuration of the endoscope within the patients's abdomen with close agreement to the X-ray image. The three dimensionality of the image has proven to be of great help in deciding the strategy for removing loops which form in the path of the endoscope during intubation. Indeed, this improvement in visualisation is likely to be of great benefit in teaching colonoscopy, as well as enabling experienced endoscopists to improve their technique when facing difficult cases. The intrinsically safe nature of the system allows it to be in continuous use throughout the examination, presenting the endoscopist with as many images as the circumstances require. This contrasts markedly with fluoroscopy which can only offer images intermittently and carries an exposure time limit for reasons of patient safety, and X-ray pictures which are essentially only a "one-shot" option. Moreover, protective clothing need not be worn by any of those present at the examination while the system is in use, nor is it necessary for the examination room to be in any way specially prepared. Indeed, the system frees such examinations from having to take place in a room apart from the ward. If need be such examinations could be carried out in complete safety and with no loss in overall integrity, at the patient's own bed in the ward.

A number of medical studies have considered the efficacy of colonoscopy as a screening methodology in asymptomatic subjects and have shown a significant detection rate for adenomas and carcinoma in subjects over the age of 60. Of particular note here is that some 50% of lesions were proximal to the splenic flexure, hence the importance of performing a total colonoscopy in such cases. The ability to conduct total colonoscopes routinely and efficiently is therefore an important objective. On the other hand it must be remembered that colonoscopy (total or otherwise) is associated with a certain morbidity and mortality due to the need to apply mechanical stress during intubation or withdrawal. The overall improvement in visualisation that the present system affords, particularly it's three dimensionality, should both raise the efficacy of total colonoscopy and reduce the risk of perforation. This in turn may also help to reduce the dosage of analgesic and sedative drugs required.

Although the application of the present positioning system to colonoscopy has been specifically addressed, the scope of the medical applications extends far beyond this by virtue of the very small size of the sensor(s). For example, bronchoscopy, gastroscopy and procedures involving a nasogastric or endotracheal tube could all utilise the sensor described herein its present catheter form. Numerous other medical applications requiring position or orientation information could benefit from either a single or multiple sensor implementation of the system.

Data gloves which facilitate the location of a wearer's hands, are used in both medical and virtual reality applications. They enable the position and direction of each of the fingers to be determined. The prior art magnetic field location system using a three coil orthogonal sensor is clearly not applicable, so current data gloves use fibre optic strain gauges. These require calibration every 2-3 minutes. The ability to locate single coil sensors means that the sensors may be wound around each joint of each finger giving a system which is less bulky, more accurate and only requires calibration during the manufacture of the gloves.

A particular area of application for the present positioning system comprises that of the so called "man-machine interface". There are numerous situations in which a human operator needs to interact with a machine, or computer, normally comprising some form of display device, examples of such interactions are with a conventional personal computer, a video conferencing system, or a virtual reality environment in which the operators field of view is filled by the display device, which in this case may be three dimensional. The present positioning system allows an operator to wear small, single coil sensors about his body to enable his movements to be detected and interpreted by a machine without the need for physical contact between the operator and the machine. For example the positioning system of the present invention could enable an operator to interact with images on a television or computer screen without the use of a conventional keyboard, mouse or stylus. The operator could wear single coil sensors on his fingertips, for example in thimbles, or a thin glove, the location and orientation of which could be detected within a magnetic field generated within the vicinity of the display screen. Linking the positioning system to the computing system would allow

the computing system to have knowledge of the position of the operators fingertips in three dimensions. A computer drawn replica of the user's hand which precisely emulates the movements of the user's own fingers, could then be utilised by the user to interact with the computer system. Thus when the user makes hand movements the virtual hand on the screen can be made to grasp and manipulate objects in the display, for example moving portions of text, rotating an engineering drawing, selecting an icon to activate a software program, etc. The virtual hand could also be used to control windows and menus and to draw diagrams. The advantage of such a man machine interface is that its use is completely intuitive, requiring no training.

Since the positioning system of the present invention enables the position of a sensor to be located in three dimensions, the extension of such a man machine interface to a three dimensional virtual reality environment is clearly possible. In this case the computer system involved may need information regarding the position of other parts of the operator' body than his hands, for example the image displayed to the operator may be dependent on the location and orientation of his head, in which case small single coil sensors can clearly be worn for example on each temple,

In a second embodiment the invention enables a sensor, comprising three orthogonal sensing coils, to be located in three dimensions relative to a single field generator comprising three orthogonal generating coils.

With reference to Figure 14, a field generator 1, comprising three generating coils 3, as previously described is mounted on a surface 2. Each generating coil is electrically connected to an amplifier 5 and is driven as previously described.

The sensor 7 in this embodiment comprises three mutually orthogonal sensing coils, A, B and C, each of which is separately electrically connected to a measurement unit 8.

In use the three generating coils are sequentially energised as previously described, but when each coil is energised the voltages induced in each of the three sensing coils V_A, V_B and V_C are measured by the measurement unit 8 and stored by the controller 6. The controller 6 then calculates from these three voltages the location of the sensor 7 relative to the single field generator 1.

The controller is able to calculate the location of the sensor, even though the axes of the generated fields have not been directed towards the sensor, by employing an algorithm which weights the voltages induced in the three sensing coils by a location dependent weighting, and then alters these weightings to achieve a calculated maximum field strength at the sensor. In order to more fully describe this algorithm the field from a single small coil is first considered.

The magnetic field produced by a small coil, from equations (A-1) and (A-2), is given by:

$$\underline{B} = \frac{k}{R^3}(2\underline{a}_R \cos\theta + \underline{a}_\theta \sin\theta) \qquad (12)$$

where

R = distance from the coil
θ = angle from the axis of the coil
k = constant for coil (size, drive current, no. turns etc).
$\underline{a}_R$ is a unit vector in the direction of B_R (see Appendix A - Fig. A-1)
$\underline{a}_\theta$ is a unit vector in the direction of B_θ (see Appendix A - Fig. A-1)

Now, the magnitude of the magnetic field

$$|\underline{B}| = \frac{k}{R^3}\sqrt{(3\cos^2\theta + 1)} \qquad (13)$$

and so it can be seen that for a given distance from the coil, the field strength is greatest when θ=0 i.e. on the axis of the coil. Clearly, if the effective axis of the coil could be directed towards the sensor, the sensor would experience a maximum in field strength.

In order to steer the effective axis of the coil without physically moving it, additional coils are required. To steer the effective axis over 3D, three coils are required in total. Assuming three mutually perpendicular coils D_x, D_y, D_z lying along each of the cartesian axes x, y and z, each coil being centred on the origin, by setting the currents to each coil as:

$$I_x = I\cos\theta\cos\phi$$

$$I_y = I \cos\theta \sin\phi$$

$$I_z = I \sin\theta$$

the effective axis of the resulting field may be steered without changing the magnitude of the field. ϕ is the angle anticlockwise from x in the xy plane, and θ is the elevation towards the z axis.

Assuming the notation of Figure 2, OP represents the effective axis of the field. That is a single drive coil, centred on the origin, with its axis along OP, fed with current I, would create the same field as the three coil arrangement with the currents I_x, I_y and I_z as described.

Thus if the field strength at the point we wished to locate could be measured, we would find that when axis OP pointed at this point, the field strength would be a maximum.

The field strength is measured using 3 orthogonal sense coils, centred on a single point. In this case an AC field must be used in the drive coils. Let the sensor coils be A, B and C, and let the amplitude of the voltages induced be V_A, V_B and V_C. The field strength can be computed from

$$B = k_s (V_A^2 + V_B^2 + V_C^2)^{1/2}$$

where k_s = a constant for the sensor and frequency used.

The effective axis of the resulting field, could be physically steered towards the sensor, and V_A, V_B, V_C monitored to maximise B. However this is difficult in practice to achieve since both θ and ϕ would need to be simultaneously altered while measurements from the sensor are taken. This leads to slow position location, and limits the system to locating a single sensor. The approach adopted in this embodiment is as follows. The drive currents for all the coils are set to I, and not to the values which would be required to physically steer the effective field axis, as discussed above. i.e.

$I_x = I$
$I_y = I$
$I_z = I$

Effectively steering of the field axis is carried out AFTER the field measurements have been made by weighting or scaling these measurements by location dependent weighting factors. Thus, instead of physically altering θ, ϕ and then measuring B, the following technique is used.

1. Switch on D_x, with $I_x = I$
2. Measure V_{ADx}, V_{BDx}, V_{CDx}
3. Switch off D_x; Switch on D_y, with $I_y = I$
4. Measure V_{ADy}, V_{BDy}, V_{CDy}
5. Switch off D_y; Switch on D_z, with $I_z = I$
6. Measure V_{ADz}, V_{BDz}, V_{CDz}
7. Switch off D_z

For the physically steered field: $I_x = I \cos\theta\cos\phi$, rather than I. The same result is achieved by weighting the results from step 3 by $\cos\theta\cos\phi$. The same logic applies to the remaining results, using the relevant weighting factor.

Thus:

$$B^2 = k_s^2(((V_{ADx}\cos\phi + V_{ADy}\sin\phi)\cos\theta + V_{ADz}\sin\theta)^2$$
$$+ ((V_{BDx}\cos\phi + V_{BDy}\sin\phi)\cos\theta + V_{BDz}\sin\theta)^2$$
$$+ ((V_{CDx}\cos\phi + V_{CDy}\sin\phi)\cos\theta + V_{CDz}\sin\theta)^2)$$

Note that the "signs" of the amplitude are important
e.g.

$$\text{phase shift} = O \Rightarrow +ve$$

$$\text{phase shift} = \pi \Rightarrow -ve$$

In this expression for B^2, θ and ϕ are the only variables.

In order to find the values of θ and ϕ which give the maximum B^2, the Gauss-Newton optimisation technique is used. This copes well with sum of squares type expressions. The expression for B^2 is well behaved, and only a few iterations are required.

In order to find the precise location of the sensor we must now find R.

If we square and sum the field magnitudes at the sensor for each generator coil, we find that:

$$\left|\underline{B}_{Dx}\right|^2 + \left|\underline{B}_{Dy}\right|^2 + \left|\underline{B}_{Dz}\right|^2 = 6\left(\frac{k_c}{R^3}\right)^2$$

and so R may be found from:

$$R^3 = k_c \sqrt{\frac{6}{\left|\underline{B}_{Dx}\right|^2 + \left|\underline{B}_{Dy}\right|^2 + \left|\underline{B}_{Dz}\right|^2}}$$

The cartesian coordinates of the sensor are then

$$x = R\cos\theta\cos\phi$$

$$y = R\cos\theta\sin\phi$$

$$z = R\sin\theta$$

As with the first embodiment the location of multiple sensors is facilitated because the generating coils are only energised sequentially allowing the generated field to be simultaneous measured at any number of locations.

Although in both embodiments of the invention described herein the voltages induced in the sensor coil 7 by the generating coils 3 are distinguished one from the other by employing a time multiplexing approach, i.e. the generating coils are energised sequentially, a frequency multiplexing approach may also be adopted within the scope of the present invention. For example in such an approach each generator coil 3 could be driven at a different frequency so that a plurality of generating coils 3 could be simultaneously energised while still allowing the voltage induced in the sensor 7 by each generating coil to be distinguished by its frequency. In such an arrangement the sensor would need to be responsive to all the energising frequencies and some form of frequency filtering would need to be provided. This filtering could be provided by discrete physical bandpass filters electrically connected to the sensor 7, or, if an A to D converter is employed as described herein, filtering of the signal from the sensor 7 can be accomplished by signal processing software in the controller 6. The use of frequency multiplexing to acquire the data for position determination can significantly increase the operating speed of the positioning system since measurements from generating coils can be taken simultaneously. Disadvantages of such a frequency multiplexing system are that it is more compiex than a time multiplexed system and requires greater electrical bandwidth. A combination of time and frequency multiplexing could of course be used.

In both embodiments it is desirable that the quasi-static magnetic field generated by a coil is established quickly and is allowed to decay quickly. For this reason it is preferred to use a first order rather than a second order drive circuit. For the generating coils employed the field settles within one cycle of being switched on.

It will be appreciated that alternative configurations of both embodiments for different applications, for example locating a sensor within a two dimensional plane, are envisaged within the scope of the present invention.

As will be clear to one skilled in this art, the roles of the generating and sensing coils may be reversed while still benefitting from the advantages of the present invention. That is the sensing coil or coils may be used as field generating elements, and the generating coils may be used as field sensing elements.

This reversal of roles has particular advantage where a static field, such as that generated by a bar magnet is employed according to the first aspect of the invention, since such a field generating element must be effectively permanently "energised". The reversal of roles allows the "sensor" permanently to generate a field which is sensed at each of the "generating elements" and the location and orientation of the "sensor" is then determined as before.

Appendix A

Consider a current, I, flowing through a small planar coil of radius, b, (Fig A-1). The frequency of I is chosen to be sufficiently low such that static field distributions apply.

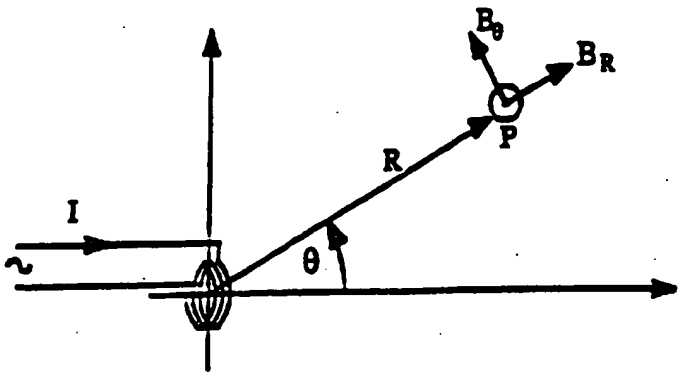


Fig A-1, Resolving magnetic flux density at a distance.

For a point P in the field whose distance R from the coil is such that R>>b, it is readily shown for example in D K Cheng, Field and Wave Electromagnetics, 2nd Ed, Addison Wesley, 1989, that

$$B_R = \frac{2\,k_c \cos\theta}{R^3} \qquad \text{(A-1)}$$

and,

$$B_\theta = \frac{k_c \sin\theta}{R^3} \qquad \text{(A-2)}$$

where k_c is a known function of I and b. B_R and B_θ represent the vector components of the magnetic flux density at point P resolved along axes parallel to the line R and the angle θ. Note that, by convention, θ is measured from the axis of the coil.

In order to resolve the magnetic flux density at P onto a 3-dimensional cartesian coordinate system, consider first the coil in the y-x plane, centred on the origin (Fig A-2).

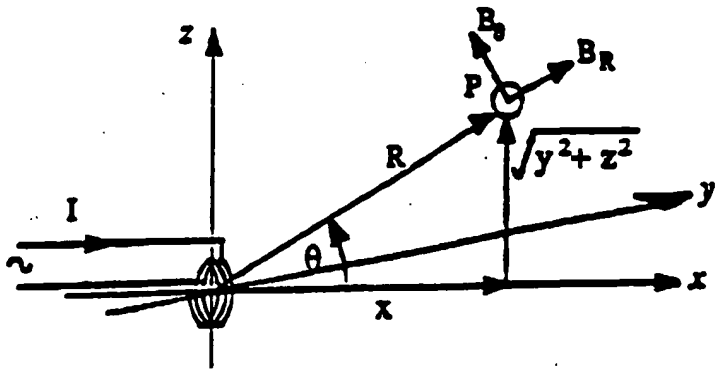


Fig A-2. Resolving magnetic flux density onto an x-y-z cartesian coordinate system.

If point P is distance x from the coil (i.e. origin) along the x-axis and its vector distance is R, the distance in the y-z plane by Pythagoras is $\sqrt{R^2 - x^2}$. Since $R^2 = x^2 + y^2 + z^2$, this distance reduces to $\sqrt{y^2 + z^2}$, as shown. It then follows that,

$$\sin\theta = \frac{\sqrt{y^2 + z^2}}{R} \qquad \text{(A-3)}$$

and,

$$\cos\theta = \frac{x}{R} \qquad \text{(A-4)}$$

Resolving the magnetic flux density at P onto a cartesian system gives, for the x-axis component,

$$B_x = B_R \cos\theta - B_\theta \sin\theta$$

From (A-1) and (A-2) this becomes,

$$B_x = \frac{k_c}{R^3}(2\cos^2\theta - \sin^2\theta)$$

and from (A-3) and (A-4),

$$B_x = \frac{k_c}{R^5}(2x^2 - y^2 - z^2) \qquad \text{(A-5)}$$

Resolving similarly onto the y-z plane gives,

$$B_{yz} = B_R \sin\phi + B_\theta \cos\phi$$

which from (A-1) and (A-2) becomes,

$$B_{yz} = \frac{k_c}{R^3}(3\cos\theta \sin\theta)$$

and from (A-3) and (A-4),

$$B_{yz} = \frac{k_c}{R^5}(3x\sqrt{y^2 + z^2}) \quad \text{(A-6)}$$

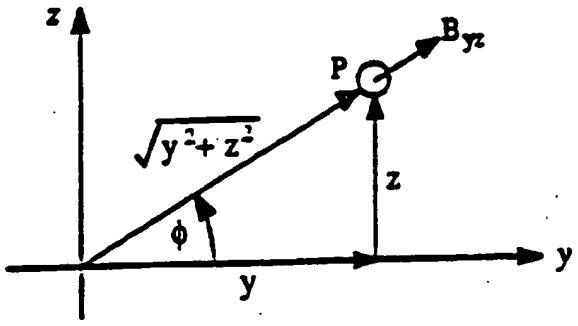


Fig A-3, Resolving the magnetic flux density at P onto the y-z plane.

Resolving the magnetic flux density at P into its y and z components (Fig A-3) gives,

$$B_y = B_{yz}\cos\phi = B_{yz}\left(\frac{y}{\sqrt{y^2 + z^2}}\right)$$

and,

$$B_z = B_{yz}\sin\phi = B_{yz}\left(\frac{z}{\sqrt{y^2 + z^2}}\right)$$

From (A-6) these become,

$$B_y = \frac{k_c}{R^5}(3xy) \quad \text{(A-7)}$$

and,

$$B_z = \frac{k_c}{R^5}(3xz) \quad \text{(A-8)}$$

For a coil (dipole) in the y-z plane, equations (A-5), (A-7) and (A-8) fully describe the resolved cartesian components of the magnetic flux density at a point P located at a radial distance R from the coil. The corresponding equations for coils in the x-y and x-z planes can be developed in an identical manner. The complete set of formulae can therefore be summarised thus.

For a coil in the y-z plane :-

$$B_x = \frac{k_c}{R^5}(2x^2 - y^2 - z^2) \quad \text{(A-9)}$$

$$B_y = \frac{k_c}{R^5}(3xy) \quad \text{(A-10)}$$

$$B_z = \frac{k_c}{R^5}(3xz) \quad \text{(A-11)}$$

For a coil in the x-y plane :-

$$B_x = \frac{k_c}{R^5}(3xz) \quad \text{(A-12)}$$

$$B_y = \frac{k_c}{R^5}(3yz) \quad \text{(A-13)}$$

$$B_z = \frac{k_c}{R^5}(2z^2 - x^2 - y^2) \quad \text{(A-14)}$$

For a coil in the x-z plane :-

$$B_x = \frac{k_c}{R^5}(3xy) \quad \text{(A-15)}$$

$$B_y = \frac{k_c}{R^5}(2y^2 - x^2 - z^2) \quad \text{(A-16)}$$

$$B_z = \frac{k_c}{R^5}(3yz) \quad \text{(A-17)}$$

Claims

1. A method of determining the location and/or orientation of a field sensor (7) relative to a plurality of field generators (1) of known location, each field generator (1) comprising a plurality of collocated field generating elements (3), each generating element (3) being energised and a measurement being made at the field sensor (7) of the respective field generated by the generating element (3), the method being characterised by the steps of:

   1)) for each field generator (1) calculating, from the measurements of the field generated by each of its generating elements (3) and an estimate of the orientation of the sensor (7), an estimate of the distance from that particular field generator (1) to the sensor (7), and
   2) utilising the estimates of distance from step 1), and the known location of the field generators (1) to calculate an estimate of the location of the sensor (7);
   3) employing the estimated location of the sensor (7) from step 2) and the measurements of the field at the sensor (7) to calculate a new estimate of the orientation of the sensor (7);
   4) repeating steps 1) to 3) iteratively, with step 1) employing the new estimate of sensor orientation from the preceding step 3), to improve the estimates of location and orientation of the sensor (7).

2. A method as claimed in claim 1, wherein each generating element (3) of each field generator (1) is energised in sequence so that only one generating element (3) is energised at any given time.

3. A method as claimed in claim 1, wherein at least two generating elements (3) are simultaneously energised, each

of these at least two generating elements (3) being energised at a different frequency from the other simultaneously energised generating element(s) (3).

4. A method as claimed in claim 1 wherein at step 3), the estimated location of the sensor (7) calculated in step 2) and the measurements of the field at the sensor (7) are used to calculate, for each field generator (1), the direction of the respective field at the sensor (7) and from these field directions calculating a new estimate of the orientation of the sensor (7).

5. A method as claimed in claim 1 or claim 4 wherein, at step 1), the initial estimate of the orientation of the sensor (7) is taken to be the orientation as calculated by the immediately preceding application of the method or, if this is the first application of the method, the axis of the sensor (7) is initially assumed to be directed towards the respective field generator (1).

6. A method of determining the location of a field sensor (7), comprising a plurality of collocated field sensing elements (A,B,C), relative to a field generator (1) comprising a plurality of collocated field generating elements (3), each field generating element (3) being energised in turn and the value of the resultant field strength being measured at the field sensor (7), the measured field strength being dependent on the location of the sensor (7) within the respective field, the method being characterised by the steps of:

1) calculating, by utilising all the values of measured field strength and an estimate of the direction of the sensor (7) from the field generator (1), a direction dependent weighting factor for each field generating element (3) so that the calculated field strength B is equal to the field strength B that would exist at the sensor (7) if the axis of the field were directed towards the sensor (7),
2) iteratively altering the direction dependent weighting factors to maximise B and thus to determine to a desired level of accuracy the direction of the sensor (7) from the field generator (1), and
3) employing the measured values of the field strength to calculate the distance of the sensor (7) from the field generator (1) and hence, from the direction of the sensor (7) in step 2), the location of the sensor (7) relative to the field generator (1).

7. A method of determining the location and/or orientation of a field generator (7) relative to a plurality of field sensors (1) of known location, each field sensor (1) comprising a plurality of collocated field sensor elements (3), the generator (7) being energised and a measurement being made at the field sensor elements (3) of the respective field generated by the generator (7), the method being characterised by the steps of:

1) for each field sensor (1) calculating, from the measurements of the field generated at each of its sensor elements (3) and an estimate of the orientation of the generator (7), an estimate of the distance from that particular sensor (1) to the generator (7), and
2) utilising the estimates of distance from step 1), and the known location of the field sensors (1) to calculate an estimate of the location of the generator (7);
3) employing the estimated location of the generator (7) from step 2) and the measurements of the field at the sensors (1) to calculate a new estimate of the orientation of the generator (7);
4) repeating steps 1) to 3) iteratively, with step 1) employing the new estimate of generator orientation from the preceding step 3), to improve the estimates of location and orientation of the generator (7).

8. Apparatus for determining the location and/or orientation of a field sensor (7) comprising:

a plurality of field generators (1) each comprising a plurality of collocated field generating elements (3),
energising means (5) operable for each field generator (1) to energise each of the plurality of field generating elements (3) to produce a field within which the location and orientation of the sensor (7) may be determined,
measurement means (8), connected to the field sensor (7), to measure and output a parameter of the field at the sensor (7), and
control means (6) to control the energising means (5), the control means (6) comprising storing means to store parameters output by the measurement means (8), and calculating means to calculate, from the stored measurements of the fields, the location and orientation of the sensor (7),
the apparatus being characterised in that the calculating means comprises:

location estimating means being operable to calculate, from the stored measurements of the fields and an estimate of the orientation of the sensor (7), an estimate of the distance of the sensor (7) from each

of the field generators (1) and, using the estimates of distance and the known location of the field generators (1), to calculate an estimate of the location of the sensor (7);
orientation estimating means being operable to calculate, from the estimate of sensor location by the location estimating means and the stored measurements of the field, a new estimate of the orientation of the sensor (7);
means to iteratively improve the estimate of the location and orientation of the sensor (7), which means in use repeatedly employ the location and orientation estimating means in sequence, wherein the output of the orientation estimating means is adopted by the location estimating means as the new estimate of sensor orientation at each iteration.

9. Apparatus for determining the location of a field sensor (7) as claimed in claim 8, wherein the field sensor (7) comprises a single field sensing element and the parameter of the field sensed by said single field sensing element is dependent on the orientation of the field sensing element within the field.

10. Apparatus for determining the location of a field sensor (7) as claimed in claim 8 or claim 9, having three field generators (1), each comprising three mutually orthogonal collocated field generating elements (3).

11. Apparatus for determining the location of an object relative to a field generator (1), the apparatus comprising

a field generator (1) comprising a plurality of field generating elements (3),
energising means (5) to sequentially energise each of the field generating elements (3) to produce a field within which the object may be located,
a sensor (7), to be attached to the object, comprising a plurality of collocated field sensing elements (A,B,C), each able to sense a parameter of the field,
measurement means (8) to measure and output the parameter of the field sensed by each field sensing element (A,B,C) when each field generating element (3) is energised, and
control means (6) to control the energising means (5), store the parameters output by the measurement means (8) and calculate the location of the sensor (7), relative to the field generator (1),
the apparatus being characterised in that the control means (6) comprises
weighting means to weight each of the parameters, sensed by the sensor (7), by a direction dependent weighting factor for each field generating element (3), so that the calculated field strength B is equal to the field strength B that would exist at the sensor (7) if the axis of the field were directed towards the sensor (7),
means to iteratively alter the direction dependent weighting factors until a maximum value of the field strength is found, and to determine the direction of the sensor (7) from the field generator (1) to a desired level of accuracy, and
calculating means to calculate the distance of the sensor (7) from the generator (1) and hence the location of the sensor (7) relative to the generator (1).

12. Apparatus for determining the location of an object as claimed in claim 11, wherein the field generator (1) comprises three mutually orthogonal field generating elements (3) and the sensor (7) comprises three mutually orthogonal field sensing elements (A,B,C).

13. Apparatus as claimed in any one of claims 8 to 12, arranged for use in surgery, therapy or diagnosis of a human or animal body.

14. An endoscopy system for use in the endoscopy of a human or animal body, the endoscopy system comprising apparatus as claimed in any one of claims 8 to 12.

15. Apparatus for monitoring the position of an endoscope within a human or animal body, the apparatus comprising a field sensor (7),

a plurality of field generators (1) each comprising a plurality of field generating elements (3),
energising means (5) operable for each field generator (1) to energise each of the plurality of field generating elements (3) to produce a field within which the location of the endoscope may be determined,
measurement means (8), connected to the field sensor (7), to measure and output a parameter of the field at the sensor (7), and
control means (6) to control the energising means (5), store parameters output by the measurement means (8), and calculate the location of the sensor (7) relative to the plurality of field generators (1), the apparatus

being characterised in that the control means (6) are arranged to calculate the location of the sensor (7) relative to the plurality of field generators (1) by the method as claimed in any one of claims 1 to 7.

16. Apparatus for determining the location and/or orientation of a sensor (7) as claimed in any one of claims 8, 9 or 10, wherein one or more of said sensors (7) are attached to parts of a glove, the output of said apparatus providing data defining the location and orientation of the respective parts of a glove wearer's hand.

17. Apparatus as claimed in claim 16, wherein one or more sensors (7) are attached to fingers of the glove.

Patentansprüche

1. Verfahren zum Bestimmen des Ortes und/oder der Orientierung eines Feldsensors (7) relativ zu mehreren Felderzeugern (1) an bekannten Orten, wobei jeder Felderzeuger (1) mehrere zusammengestellte felderzeugende Elemente (3) enthält, wobei jedes erzeugende Element (3) eingeschaltet wird und bei dem Feldsensor (7) eine Messung des jeweiligen durch das erzeugende Element (3) erzeugten Feldes ausgeführt wird, wobei das Verfahren gekennzeichnet ist durch die folgenden Schritte:

   1) für jeden Felderzeuger (1) Berechnen einer Abschätzung der Entfernung von jenem besonderen Felderzeuger (1) zu dem Sensor (7) aus den Messungen des durch jedes seiner erzeugenden Elemente (3) erzeugten Feldes und einer Abschätzung der Orientierung des Sensors (7), und
   2) Verwenden der Entfernungsabschätzungen aus Schritt 1) und des bekannten Ortes des Felderzeugers (1) zum Berechnen einer Abschätzung des Ortes des Sensors (7);
   3) Verwenden des abgeschätzten Ortes des Sensors (7) aus Schritt 2) und der Messungen des Feldes bei dem Sensor (7) zum Berechnen einer neuen Abschätzung der Orientierung des Sensors (7);
   4) iteratives Wiederholen der Schritte 1) bis 3) unter Verwendung der neuen Abschätzung der Sensororientierung aus dem vorausgehenden Schritt 3) in Schritt 1) zum Verbessern der Abschätzungen des Ortes und der Orientierung des Sensors (7).

2. Verfahren nach Anspruch 1, bei dem jedes erzeugende Element (3) jedes Felderzeugers (1) sequentiell eingeschaltet wird, so daß zu irgendeiner gegebenen Zeit nur ein erzeugendes Element (3) eingeschaltet ist.

3. Verfahren nach Anspruch 1, bei dem zumindest zwei erzeugende Elemente (3) gleichzeitig eingeschaltet werden, wobei jedes dieser zwei erzeugenden Elemente (3) bei einer von dem (den) anderen gleichzeitig eingeschalteten erzeugenden Element(en) (3) verschiedenen Frequenz eingeschaltet wird.

4. Verfahren nach Anspruch 1, bei dem im Schritt 3) der in Schritt 2) berechnete geschätzte Ort des Sensors (7) und die Messungen des Feldes bei dem Sensor (7) verwendet werden, um für jeden Felderzeuger (1) die Richtung des jeweiligen Feldes bei dem Sensor (7) zu berechnen und aus diesen Feldrichtungen eine neue Abschätzung der Orientierung des Sensors (7) zu berechnen.

5. Verfahren nach Anspruch 1 oder Anspruch 4, bei dem bei Schritt 1) als Anfangsabschätzung der Orientierung des Sensors (7) die durch die unmittelbar vorausgehende Anwendung des Verfahrens berechnete Orientierung genommen wird oder, falls dies die erste Anwendung des Verfahrens ist, die Achse des Sensors (7) anfangs als zum entsprechenden Felderzeuger (1) gerichtet angenommen wird.

6. Verfahren zum Bestimmen des Ortes eines Feldsensors (7) mit mehreren relativ zu einem Felderzeuger (1) zusammengestellten Feldsensorelementen (A, B, C) mit mehreren zusammengestellten felderzeugenden Elementen (3), wobei jedes felderzeugende Element (3) der Reihe nach eingeschaltet wird und der Wert der resultierenden Feldstärke bei dem Feldsensor (7) gemessen wird, wobei die gemessene Feldstärke von dem Ort des Sensors (7) innerhalb des jeweiligen Feldes abhängt, wobei das Verfahren gekennzeichnet ist durch die folgenden Schritte:

   1) Berechnen eines richtungsabhängigen Gewichtungsfaktors für jedes felderzeugende Element (3), so daß die berechnete Feldstärke B gleich der Feldstärke B ist, die bei dem Sensor (7) vorhanden wäre, wenn die Achse des Feldes zum Sensor (7) gerichtet wäre, unter Verwendung aller Werte der gemessenen Feldstärke und einer Abschätzung der Richtung des Sensors (7) von dem Felderzeuger (1),
   2) iteratives Ändern der richtungsabhängigen Gewichtungsfaktoren, um B zu maximieren und daher die Richtung des Sensors (7) von dem Felderzeuger (1) bis zu einem gewünschten Genauigkeitsgrad zu bestimmen,

und
3) Verwenden der gemessenen Werte der Feldstärke zum Berechnen der Entfernung des Sensors (7) von dem Felderzeuger (1) und daher aus der Richtung des Sensors (7) in Schritt 2) des Ortes des Sensors (7) relativ zu dem Felderzeuger (1).

7. Verfahren zum Bestimmen des Ortes und/oder der Orientierung eines Felderzeugers (7) relativ zu mehreren Feldsensoren (1) an bekannten Orten, wobei jeder Feldsensor (1) mehrere zusammengestellte Feldsensorelemente (3) enthält, wobei der Generator (7) eingeschaltet wird und wobei eine Messung des jeweiligen durch den Erzeuger (7) erzeugten Feldes bei den Feldsensorelementen (3) ausgeführt wird, wobei das Verfahren gekennzeichnet ist durch die folgenden Schritte:

1) für jeden Feldsensor (1) Berechnen einer Abschätzung der Entfernung von jenem besonderen Sensor (1) zu dem Erzeuger (7) aus den Messungen des bei jedem seiner Sensorelemente (3) erzeugten Feldes und einer Abschätzung der Orientierung des Generators (7), und
2) Verwenden der Abschätzungen der Entfernung aus Schritt 1) und des bekannten Ortes des Feldsensors (1) zum Berechnen einer Abschätzung des Ortes des Generators (7);
3) Verwenden des geschätzten Ortes des Erzeugers (7) aus Schritt 2) und der Messungen des Feldes bei den Sensoren (1) zum Berechnen einer neuen Abschätzung der Orientierung des Erzeugers (7);
4) iteratives Wiederholen der Schritte 1) bis 3), wobei in Schritt 1) zum Verbessern der Abschätzungen des Ortes und der Orientierung des Erzeugers (7) die neue Abschätzung der Orientierung des Erzeugers von dem vorausgehenden Schritt 3) verwendet wird.

8. Vorrichtung zum Bestimmen des Ortes und/oder der Orientierung eines Feldsensors (7), mit:

mehreren Felderzeugern (1), wobei jeder mehrere zusammengestellte felderzeugende Elemente (3) enthält,
einer Einschalteinrichtung (5), die für jeden Felderzeuger (1) so betrieben werden kann, daß sie mehrere felderzeugende Elemente (3) zum Erzeugen eines Feldes, innerhalb dessen der Ort und die Orientierung des Sensors (7) bestimmt werden können, einschalten kann,
einer an den Feldsensor (7) angeschlossenen Meßeinrichtung (8) zum Messen und Ausgeben eines Parameters des Feldes bei dem Sensor (7), und
einer Steuereinrichtung (6) zum Steuern der Einschalteinrichtung (5), wobei die Steuereinrichtung (6) eine Speichereinrichtung zum Speichern von durch die Meßeinrichtung (8) ausgegebenen Parametern und eine Recheneinrichtung zum Berechnen des Ortes und der Orientierung des Sensors (7) aus den gespeicherten Messungen des Feldes enthalten,
wobei die Vorrichtung dadurch gekennzeichnet ist, daß die Recheneinrichtung folgendes enthält:
eine Ortsabschätzungseinrichtung, die so betrieben werden kann, daß sie aus den gespeicherten Messungen der Felder und einer Abschätzung der Orientierung des Sensors (7) eine Abschätzung der Entfernung des Sensors (7) von jedem Felderzeuger (1) berechnen kann und unter Verwendung der Abschätzungen der Entfernung und des bekannten Ortes des Felderzeugers (1) eine Abschätzung des Ortes des Sensors (7) berechnen kann;
eine Orientierungsabschätzungseinrichtung, die so betrieben werden kann, daß sie aus der Abschätzung des Sensorortes durch die Ortsabschätzungseinrichtung und die gespeicherten Messungen des Feldes eine neue Abschätzung der Orientierung des Sensors (7) berechnen kann;
eine Einrichtung zum iterativen Verbessern der Abschätzung des Ortes und der Orientierung des Sensors (7), wobei diese Einrichtung beim Gebrauch wiederholt sequentiell die Orts- und Orientierungsabschätzungseinrichtung verwendet, bei dem die Ausgangsgrößen der Orientierungsabschätzungseinrichtung bei jeder Iteration von der Ortsabschätzungseinrichtung als die neue Abschätzung der Sensororientierung verwendet werden.

9. Vorrichtung zum Bestimmen des Ortes eines Feldsensors (7) nach Anspruch 8, bei dem der Feldsensor (7) ein einzelnes Feldsensorelement enthält und bei dem der durch das einzelne Feldsensorelement abgetastete Parameter des Feldes von der Orientierung des Feldsensorelements innerhalb des Feldes abhängt.

10. Vorrichtung zum Bestimmen des Ortes eines Feldsensors (7) nach Anspruch 8 oder Anspruch 9 mit drei Felderzeugern (1), von denen jeder drei zueinander orthogonale zusammengestellte felderzeugende Elemente (3) enthält.

11. Vorrichtung zum Bestimmen des Ortes eines Objekts relativ zu einem Felderzeuger (1), wobei die Vorrichtung

enthält:

einen Felderzeuger (1) mit mehreren felderzeugenden Elementen (3),
eine Einschalteinrichtung (5) zum sequentiellen Einschalten jedes der felderzeugenden Elemente (3) zum Erzeugen eines Feldes, innerhalb dessen das Objekt lokalisiert werden kann,
einen an dem Objekt anzubringenden Sensor (7) mit mehreren zusammengestellten Feldsensorelementen (A, B, C), die jeweils einen Parameter des Feldes abtasten können,
eine Meßeinrichtung (8) zum Messen und Ausgeben des Parameters des durch jedes Feldsensorelement (A, B, C) abgetasteten Feldes, wenn jedes felderzeugende Element (3) eingeschaltet ist, und
eine Steuereinrichtung (6) zum Steuern der Einschalteinrichtung (5), zum Speichern der durch die Meßeinrichtung (8) ausgegebenen Parameter und zum Berechnen des Ortes des Sensors (7) relativ zu dem Felderzeuger (1),

wobei die Vorrichtung dadurch gekennzeichnet ist, daß die Steuereinrichtung (6) enthält:

eine Gewichtungseinrichtung zum Gewichten jedes der von dem Sensor (7) abgetasteten Parameter durch einen richtungsabhängigen Gewichtungsfaktor für jedes felderzeugende Element (3), so daß die berechnete Feldstärke B gleich der Feldstärke B ist, die bei dem Sensor (7) existieren würde, falls die Achse des Feldes zum Sensor (7) gerichtet wäre,
eine Einrichtung zum iterativen Ändern der richtungsabhängigen Gewichtungsfaktoren, bis ein Maximalwert der Feldstärke gefunden ist, und zum Bestimmen der Richtung des Sensors (7) von dem Felderzeuger (1) bis zu einem gewünschten Genauigkeitsgrad, und
eine Recheneinrichtung zum Berechnen der Entfernung des Sensors (7) von dem Erzeuger (1) und daher des Ortes des Sensors (7) relativ zu dem Erzeuger (1).

12. Vorrichtung zum Bestimmen des Ortes eines Objekts nach Anspruch 11, bei dem der Felderzeuger (1) drei zueinander orthogonale felderzeugende Elemente (3) enthält und der Sensor (7) drei zueinander orthogonale Feldsensorelemente (A, B, C) enthält.

13. Vorrichtung nach irgendeinem der Ansprüche 8 bis 12, die so beschaffen ist, daß sie in der Chirurgie, Therapie oder Diagnose eines menschlichen oder tierischen Körpers verwendet wird.

14. Endoskopiesystem zur Verwendung in der Endoskopie eines menschlichen oder tierischen Körpers, wobei das Endoskopiesystem eine in irgendeinem der Ansprüche 8 bis 12 beanspruchte Vorrichtung enthält.

15. Vorrichtung zum Überwachen des Ortes eines Endoskops innerhalb eines menschlichen oder tierischen Körpers, wobei die Vorrichtung versehen ist mit einem Feldsensor (7),

mehreren Felderzeuger (1), wovon jeder mehrere felderzeugende Elemente (3) enthält,
einer Einschalteinrichtung (5), die für jeden Felderzeuger (1) so betrieben werden kann, daß sie jedes der mehreren felderzeugenden Elemente (3) zum Erzeugen eines Feldes, innerhalb dessen der Ort des Endoskops bestimmt werden kann, einschalten kann,
einer an den Feldsensor (7) angeschlossenen Meßeinrichtung (8) zum Messen und Ausgeben eines Parameters des Feldes bei dem Sensor (7), und
einer Steuereinrichtung (6) zum Steuern der Einschalteinrichtung (5), zum Speichern der durch die Meßeinrichtung (8) ausgegebenen Parameter und zum Berechnen des Ortes des Sensors (7) relativ zu den mehreren Felderzeugern (1), wobei die Vorrichtung dadurch gekennzeichnet ist, daß die Steuereinrichtung (6) so beschaffen ist, daß sie den Ort des Sensors (7) relativ zu den mehreren Felderzeugern (1) mit dem in irgendeinem der Ansprüche 1 bis 7 beanspruchten Verfahren berechnet.

16. Vorrichtung zum Bestimmen des Ortes und/oder der Orientierung eines Sensors (7) nach irgendeinem der Ansprüche 8, 9 oder 10, bei dem einer oder mehrere der Sensoren (7) an Teilen eines Handschuhs befestigt sind, wobei der Ausgang der Vorrichtung Daten bereitstellt, die den Ort und die Orientierung der jeweiligen Teile der Hand eines Trägers des Handschuhs definieren.

17. Vorrichtung nach Anspruch 16, bei dem einer oder mehrere Sensoren (7) an Fingern des Handschuhs befestigt sind.

Revendications

1. Procédé de détermination de la localisation et/ou de l'orientation d'un capteur de champ (7) par rapport à une pluralité de générateurs de champ (1) de localisation connue, chaque générateur de champ (1) comprenant une pluralité d'éléments de génération de champ situés au même emplacement (3), chaque élément de génération (3) étant activé et une mesure étant faite au niveau du capteur de champ (7) du champ respectif généré par l'élément de génération (3), le procédé étant caractérisé par les étapes consistant à :

   1) pour chaque générateur de champ (1), calculer à partir des mesures du champ généré par chacun de ses éléments de génération (3) et d'une estimation de l'orientation du capteur (7), une estimation de la distance entre ce générateur de champ particulier (1) et le capteur (7), et
   2) utiliser les estimations de la distance provenant de l'étape 1), et la localisation connue des générateurs de champ (1) pour calculer une estimation de la localisation du capteur (7),
   3) utiliser la localisation estimée du capteur (7) provenant de l'étape 2) et les mesures du champ au niveau du capteur (7) pour calculer une nouvelle estimation de l'orientation du capteur (7),
   4) répéter les étapes 1) à 3) de façon itérative, l'étape 1) utilisant la nouvelle estimation de l'orientation du capteur provenant de l'étape précédente 3), afin d'améliorer les estimations de la localisation et de l'orientation du capteur (7).

2. Procédé selon la revendication 1, dans lequel chaque élément de génération (3) de chaque générateur de champ (1) est activé en séquence de sorte qu'un seul élément de génération (3) est activé à un instant donné.

3. Procédé selon la revendication 1, dans lequel au moins deux éléments de génération (3) sont activés simultanément, chacun de ces au moins deux éléments de génération (3) étant activé à une fréquence différente de l'autre ou des autres éléments de génération activés simultanément (3).

4. Procédé selon la revendication 1, dans lequel à l'étape (3), la localisation estimée du capteur (7) calculée à l'étape (2) et les mesures du champ au niveau du capteur (7) sont utilisées pour calculer, pour chaque générateur de champ (1), la direction du champ respectif au niveau du capteur (7) et, à partir de ces directions de champ, calculer une nouvelle estimation de l'orientation du capteur (7).

5. Procédé selon la revendication 1 ou la revendication 4, dans lequel à l'étape (1), l'estimation initiale de l'orientation du capteur (7) est prise comme étant l'orientation qui a été calculée par l'application immédiatement précédente du procédé ou, s'il s'agit de la première application du procédé, l'axe du capteur (7) est supposé initialement être orienté en direction du générateur de champ respectif (1).

6. Procédé de détermination de la localisation d'un capteur de champ (7), comprenant une pluralité d'éléments de détection de champ situés au même emplacement (A, B, C) par rapport à un générateur de champ (1) comprenant une pluralité d'éléments de génération de champ situés au même emplacement (3), chaque élément de génération de champ (3) étant activé tour à tour et la valeur de l'intensité du champ résultant étant mesurée au niveau du capteur de champ (7), l'intensité du champ mesurée étant dépendante de la localisation du capteur (7) à l'intérieur du champ respectif, le procédé étant caractérisé par les étapes consistant à :

   1) calculer, en utilisant toutes les valeurs d'intensité de champ mesurées et une estimation de la direction du capteur (7) par rapport au générateur de champ (1), un facteur de pondération dépendant de la direction pour chaque élément de génération de champ (3) de sorte que l'intensité de champ calculée B soit égale à l'intensité du champ B qui existerait au niveau du capteur (7) si l'axe du champ était orienté en direction du capteur (7),
   2) modifier de façon itérative les facteurs de pondération dépendant de la direction afin de maximiser B et de déterminer ainsi avec un niveau désiré de précision la direction du capteur (7) par rapport au générateur de champ (1), et
   3) utiliser les valeurs mesurées de l'intensité du champ pour calculer la distance du capteur (7) par rapport au générateur de champ (1) et de ce fait, à partir de la direction du capteur (7) de l'étape 2), la localisation du capteur (7) par rapport au générateur de champ (1).

7. Procédé de détermination de la localisation et/ou de l'orientation d'un générateur de champ (7) par rapport à une pluralité de capteurs de champ (1) de localisation connue, chaque capteur de champ (1) comprenant une pluralité d'éléments de capteur de champ situés au même emplacement (3), le générateur (7) étant activé et une mesure étant faite au niveau des éléments de capteur de champ (3) du champ respectif généré par le générateur (7), le

procédé étant caractérisé par les étapes consistant à :

1) pour chaque capteur de champ (1), calculer à partir des mesures du champ généré au niveau de chacun de ses éléments de capteur (3) et d'une estimation de l'orientation du générateur (7), une estimation de la distance entre ce capteur particulier(1) et le générateur (7), et
2) utiliser les estimations de distance provenant de l'étape 1), et la localisation connue des capteurs de champ (1) pour calculer une estimation de la localisation du générateur (7),
3) utiliser la localisation estimée du générateur (7) provenant de l'étape 2) et les mesures du champ au niveau des capteurs (1) pour calculer une nouvelle estimation de l'orientation du générateur (7),
4) répéter les étapes 1) à 3) de façon itérative, l'étape 1) utilisant la nouvelle estimation de l'orientation du générateur provenant de l'étape précédente 3), afin d'améliorer les estimations de la localisation et de l'orientation du générateur (7).

8. Dispositif destiné à déterminer la localisation et/ou l'orientation d'un capteur de champ (7) comprenant :

une pluralité de générateurs de champ (1) comprenant chacun une pluralité d'éléments de génération de champ situés au même emplacement (3),
un moyen d'activation (5) pouvant être mis en oeuvre pour chaque générateur de champ (1) afin d'activer chacun de la pluralité des éléments de génération de champ (3) de manière à produire un champ à l'intérieur duquel la localisation et l'orientation du capteur (7) peuvent être déterminées,
un moyen de mesure (8), relié au capteur de champ (7), afin de mesurer et de fournir en sortie un paramètre du champ au niveau du capteur (7), et
un moyen de commande (6) afin de commander le moyen d'activation (5), le moyen de commande (6) comprenant un moyen de mémorisation destiné à mémoriser des paramètres fournis en sortie par le moyen de mesure (8), et un moyen de calcul destiné à calculer, à partir des mesures mémorisées des champs, la localisation et l'orientation du capteur (7), le dispositif étant caractérisé en ce que le moyen de calcul comprend :

un moyen d'estimation de localisation qui peut être mis en oeuvre pour calculer, à partir des mesures mémorisées des champs et d'une estimation de l'orientation du capteur (7), une estimation de la distance du capteur (7) par rapport à chacun des générateurs de champ (1) et, en utilisant les estimations de distance et la localisation connue des générateurs de champ (1), calculer une estimation de la localisation du capteur (7),
un moyen d'estimation d'orientation qui peut être mis en oeuvre pour calculer, à partir de l'estimation de la localisation du capteur par le moyen d'estimation de localisation et des mesures mémorisées du champ, une nouvelle estimation de l'orientation du capteur (7),
un moyen destiné à améliorer de façon itérative l'estimation de la localisation et de l'orientation du capteur (7), lequel moyen, en utilisation, utilise de façon répétitive les moyens d'estimation de localisation et d'orientation en séquence, dans lequel la sortie du moyen d'estimation d'orientation est adoptée par le moyen d'estimation de localisation en tant que nouvelle estimation de l'orientation du capteur à chaque itération.

9. Dispositif destiné à déterminer la localisation d'un capteur de champ (7) selon la revendication 8, dans lequel le capteur de champ (7) comprend un élément de détection de champ unique et le paramètre du champ détecté par ledit élément de détection de champ unique dépend de l'orientation de l'élément de détection de champ à l'intérieur du champ.

10. Dispositif destiné à déterminer la localisation d'un capteur de champ (7) selon la revendication 8 ou la revendication 9, comportant trois générateurs de champ (1), chacun comprenant trois éléments de génération de champ situés au même emplacement mutuellement orthogonaux (3).

11. Dispositif destiné à déterminer la localisation d'un objet par rapport à un générateur de champ (1), le dispositif comprenant

un générateur de champ (1) comprenant une pluralité d'éléments de génération de champ (3),
un moyen d'activation (5) destiné à activer séquentiellement chacun des éléments de génération de champ (3) afin de produire un champ à l'intérieur duquel l'objet peut être localisé,
un capteur (7), destiné à être fixé à l'objet, comprenant une pluralité d'éléments de détection de champ situés au même emplacement (A, B, C), chacun pouvant détecter un paramètre du champ,

un moyen de mesure (8) destiné à mesurer et à fournir en sortie le paramètre du champ détecté par chaque élément de détection de champ (A, B, C) lorsque chaque élément de génération de champ (3) est activé, et un moyen de commande (6) destiné à commander le moyen d'activation (5), à mémoriser les paramètres fournis en sortie par le moyen de mesure (8) et à calculer la localisation du capteur (7)..par rapport au générateur de champ (1),
le dispositif étant caractérisé en ce que le moyen de commande (6) comprend
un moyen de pondération destiné à pondérer chacun des paramètres, détectés par le capteur (7), par un facteur de pondération dépendant de la direction pour chaque élément de génération de champ (3), de sorte que l'intensité calculée du champ B soit égale à l'intensité du champ B qui existerait au niveau du capteur (7) si l'axe du champ était orienté en direction du capteur (7),
un moyen destiné à modifier de façon itérative les facteurs de pondération dépendants de la direction jusqu'à ce qu'une valeur maximum de l'intensité du champ soit trouvée, et à déterminer la direction du capteur (7) par rapport au générateur de champ (1) avec un niveau désiré de précision, et
un moyen de calcul destiné à calculer la distance du capteur (7) par rapport au générateur (1) et de ce fait la localisation du capteur (7) par rapport au générateur (1).

12. Dispositif destiné à déterminer la localisation d'un objet selon la revendication 11, dans lequel le générateur de champ (1) comprend trois éléments de génération de champ mutuellement orthogonaux (3) et le capteur (7) comprend trois éléments de détection de champ mutuellement orthogonaux (A, B, C).

13. Dispositif selon l'une quelconque des revendications 8 à 12, agencé pour une utilisation en chirurgie, thérapie ou diagnostic d'un corps humain ou animal.

14. Système d'endoscopie destiné à être utilisé lors de l'endoscopie d'un corps humain ou animal, le système d'endoscopie comprenant un dispositif selon l'une quelconque des revendications 8 à 12.

15. Dispositif destiné à contrôler la position d'un endoscope à l'intérieur d'un corps humain ou animal, le dispositif comprenant un capteur de champ (7),

une pluralité de générateurs de champ (1) comprenant chacun une pluralité d'éléments de génération de champ (3),
un moyen d'activation (5) pouvant être mis en oeuvre pour chaque générateur de champ (1) afin d'activer chacun de la pluralité des éléments de génération de champ (3) de manière à produire un champ à l'intérieur duquel la localisation de l'endoscope peut être déterminée,
un moyen de mesure (8) relié au capteur de champ (7), afin de mesurer et de fournir en sortie un paramètre du champ au niveau du capteur (7), et
un moyen de commande (6) destiné à commander le moyen d'activation (5), mémoriser les paramètres fournis en sortie par le moyen de mesure (8), et calculer la localisation du capteur (7) par rapport à la pluralité des générateurs de champ (1), le dispositif étant caractérisé en ce que le moyen de commande (6) est agencé pour calculer la localisation du capteur (7) par rapport à la pluralité des générateurs de champ (1) grâce au procédé selon l'une quelconque des revendications 1 à 7.

16. Dispositif destiné à déterminer la localisation et/ou l'orientation d'un capteur (7) selon l'une quelconque des revendications 8, 9 ou 10, dans lequel un ou plusieurs desdits capteurs (7) sont fixés à des parties d'un gant, la sortie dudit dispositif procurant des données qui définissent la localisation et l'orientation des diverses parties de la main du porteur du gant.

17. Dispositif selon la revendication 16, dans lequel un ou plusieurs capteurs (7) sont fixés aux doigts du gant.

Fig.1.

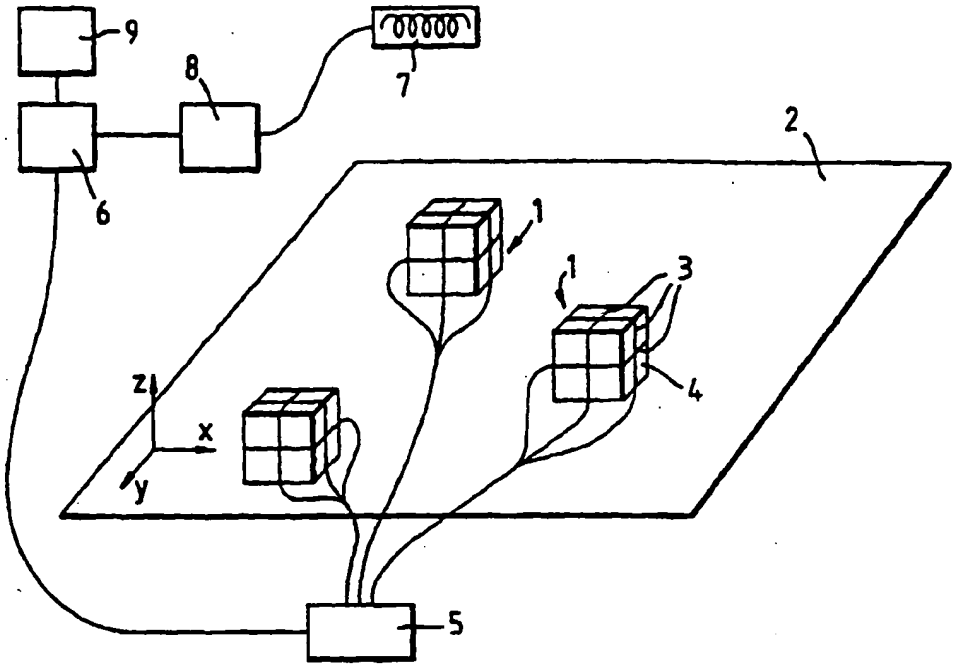


Fig.14.

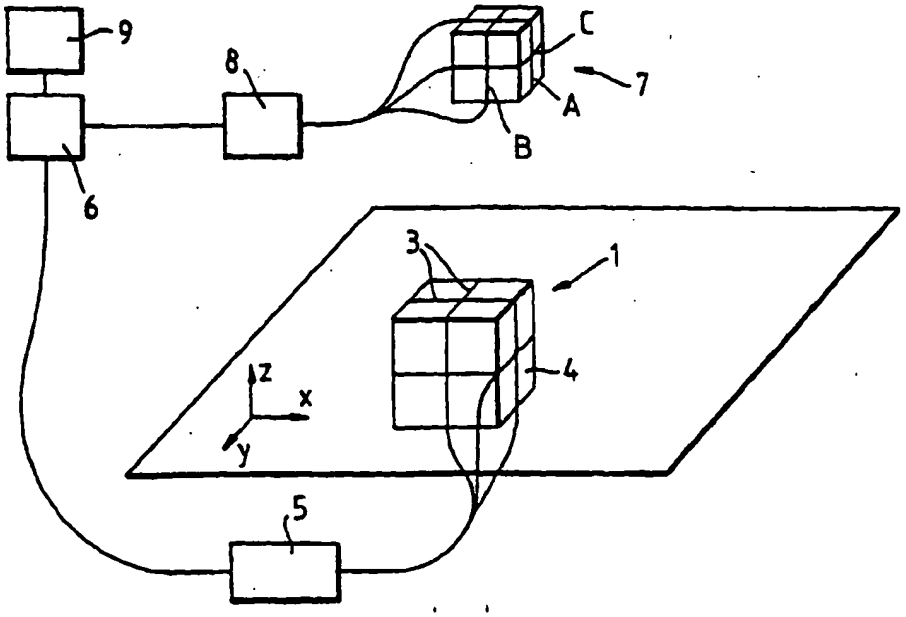


Fig.2.

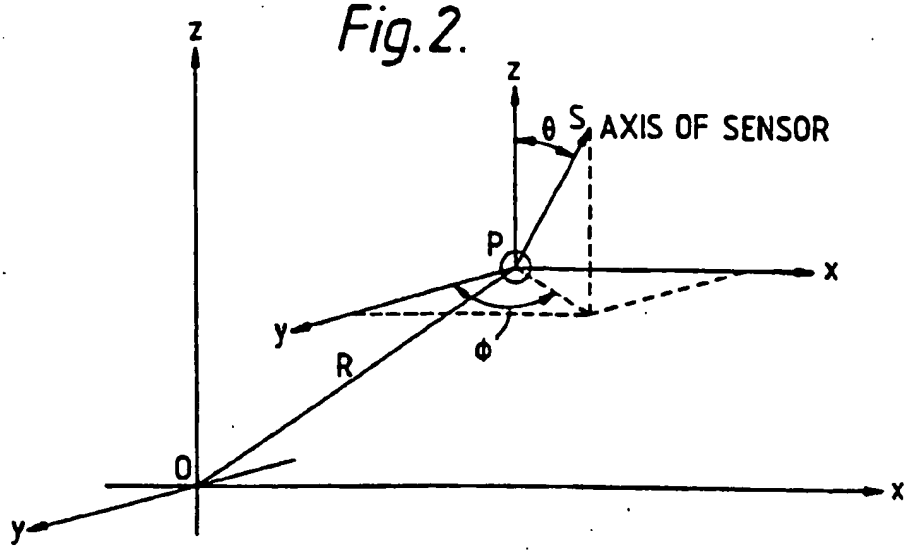


Fig.3.

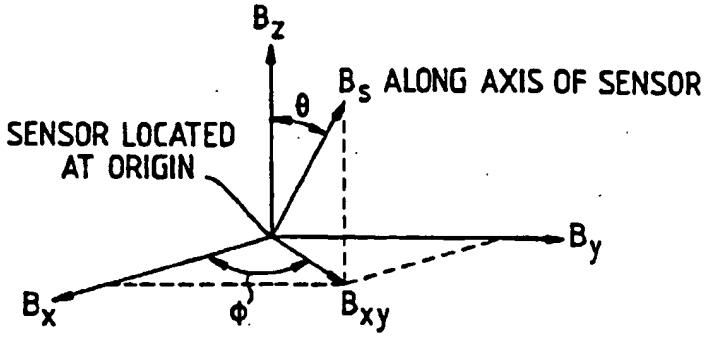


Fig.4.

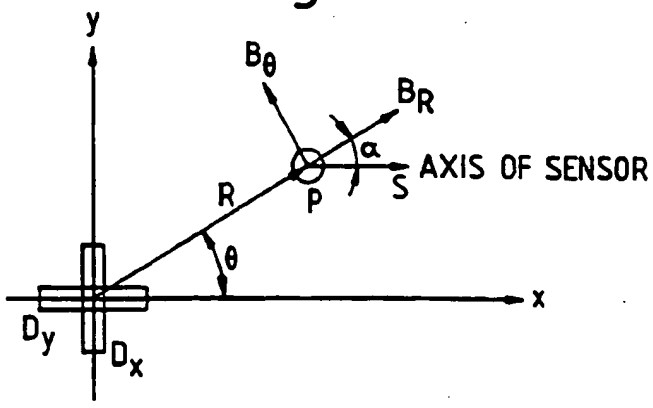


Fig.5.

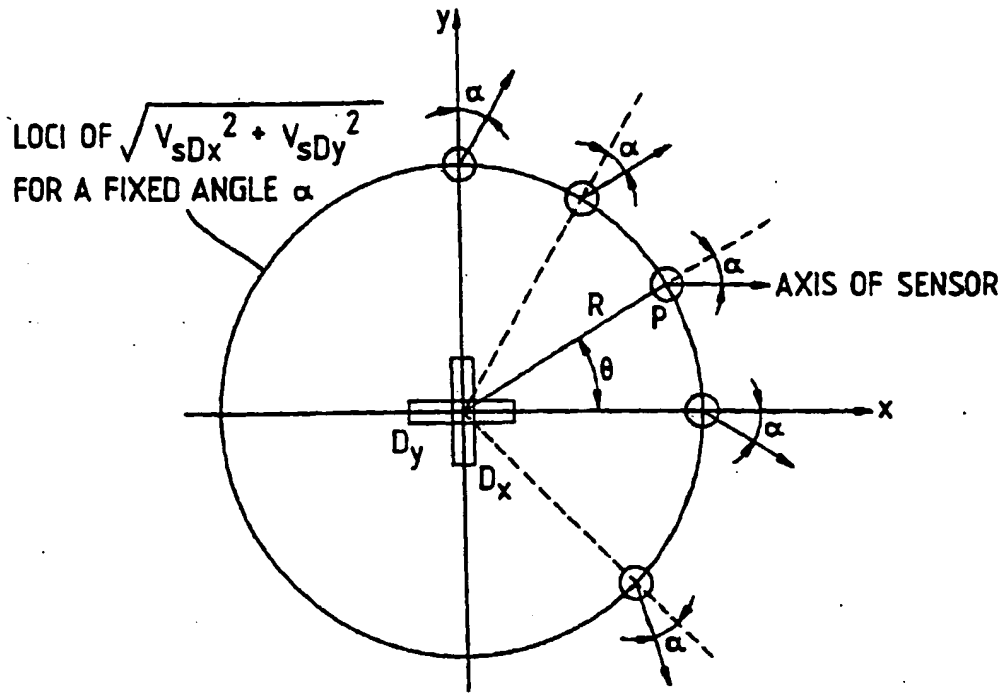

y
LOCI OF $\sqrt{V_{sDx}^2 + V_{sDy}^2}$
FOR A FIXED ANGLE α
α
AXIS OF SENSOR
R
P
θ
x
D_y
D_x

Fig.6.

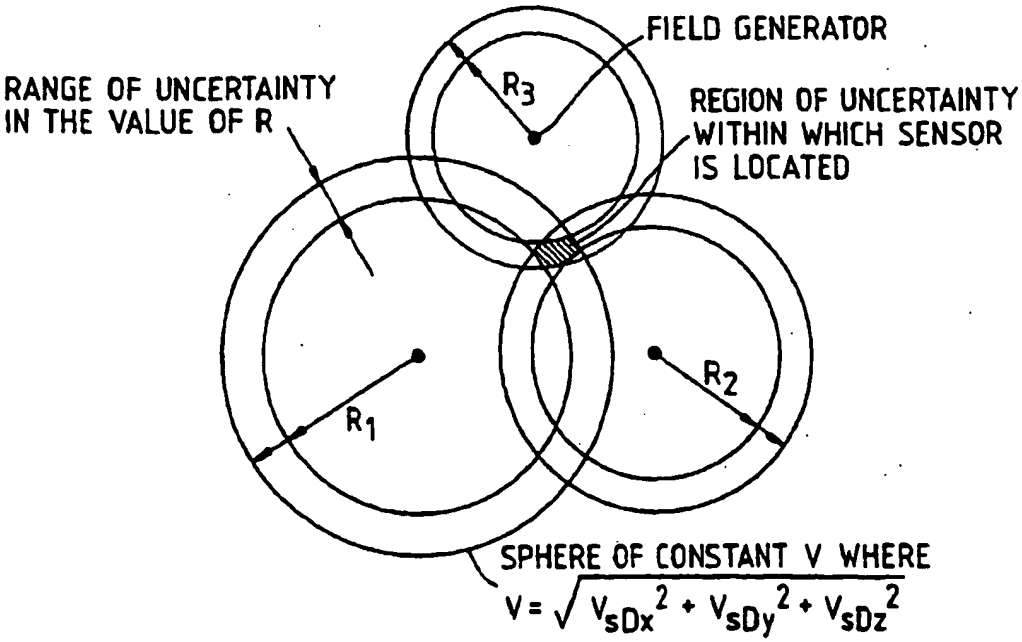

FIELD GENERATOR
RANGE OF UNCERTAINTY
IN THE VALUE OF R
R_3
REGION OF UNCERTAINTY
WITHIN WHICH SENSOR
IS LOCATED
R_1
R_2
SPHERE OF CONSTANT V WHERE
$V = \sqrt{V_{sDx}^2 + V_{sDy}^2 + V_{sDz}^2}$

Fig.7.

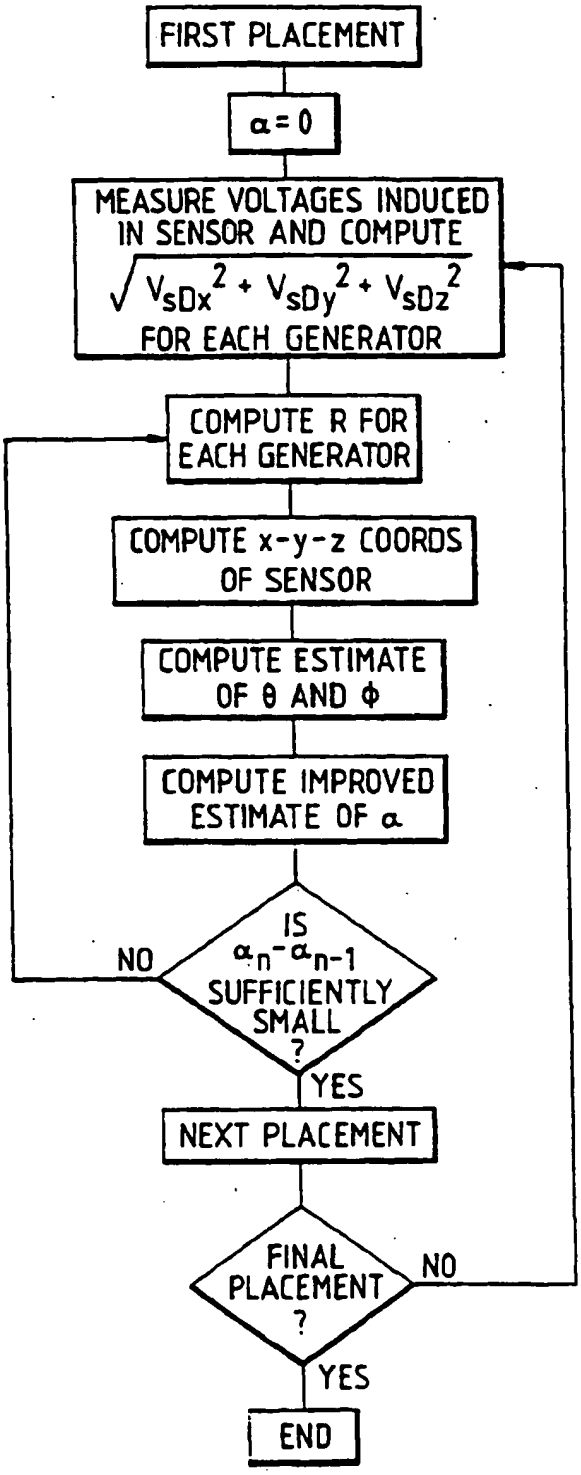

FIRST PLACEMENT
α = 0
MEASURE VOLTAGES INDUCED IN SENSOR AND COMPUTE
$\sqrt{V_{sDx}^2 + V_{sDy}^2 + V_{sDz}^2}$
FOR EACH GENERATOR
COMPUTE R FOR EACH GENERATOR
COMPUTE x-y-z COORDS OF SENSOR
COMPUTE ESTIMATE OF θ AND φ
COMPUTE IMPROVED ESTIMATE OF α
IS $\alpha_n - \alpha_{n-1}$ SUFFICIENTLY SMALL ?
NO
YES
NEXT PLACEMENT
FINAL PLACEMENT ?
NO
YES
END

Fig. 8.

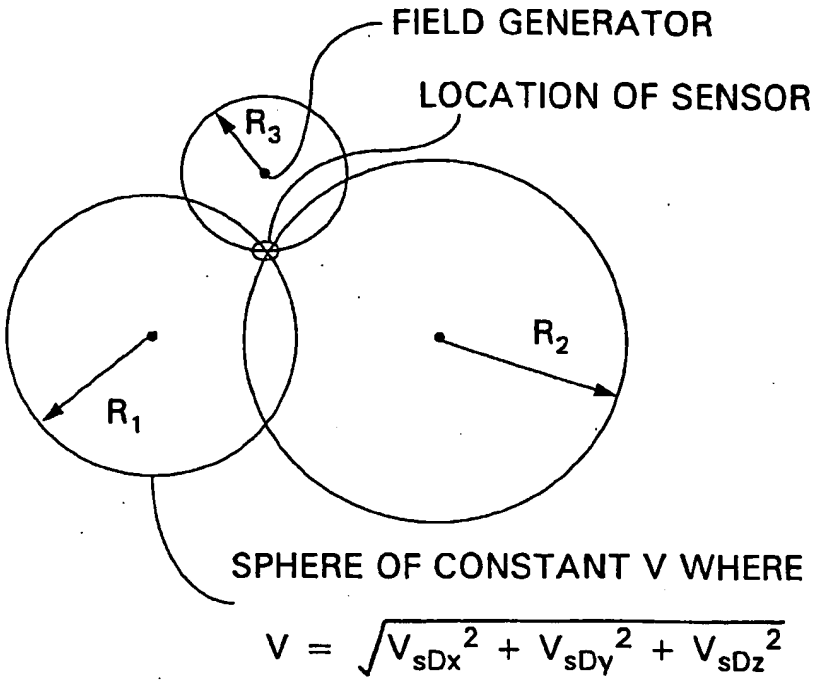

FIELD GENERATOR
LOCATION OF SENSOR
R3
R2
R1
SPHERE OF CONSTANT V WHERE
V = √(VsDx² + VsDy² + VsDz²)

Fig. 9.

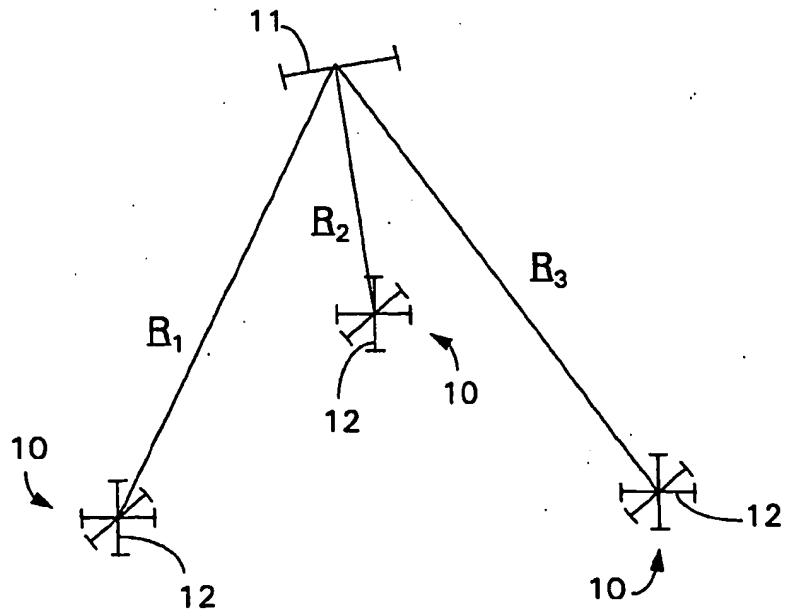

11
R2
R3
R1
10
12
10
12
12
10

Fig. 10.

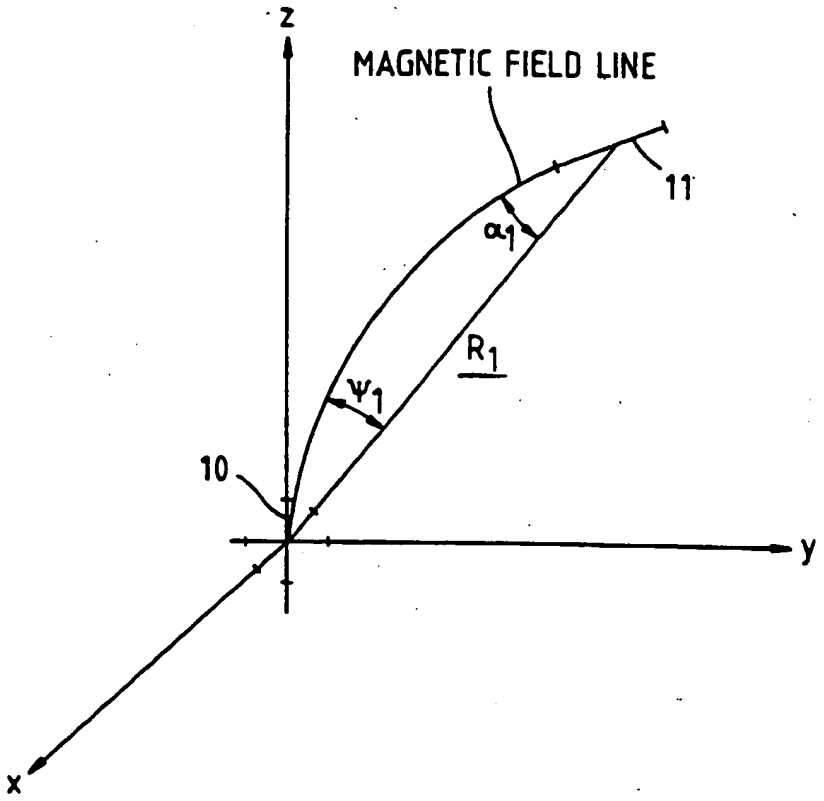
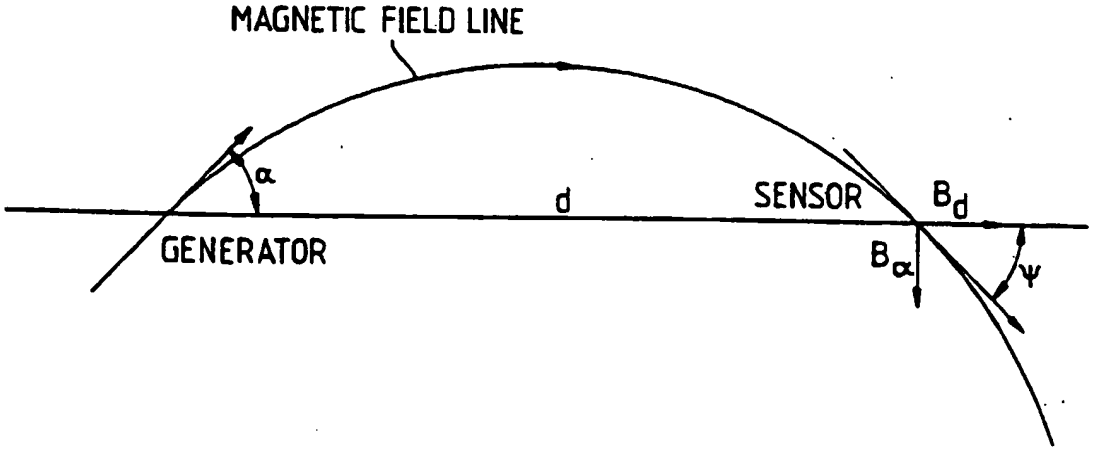

z
MAGNETIC FIELD LINE
11
α_1
R_1
Ψ_1
10
y
x

Fig. 11.


MAGNETIC FIELD LINE
α
d
SENSOR
B_d
GENERATOR
B_α
Ψ

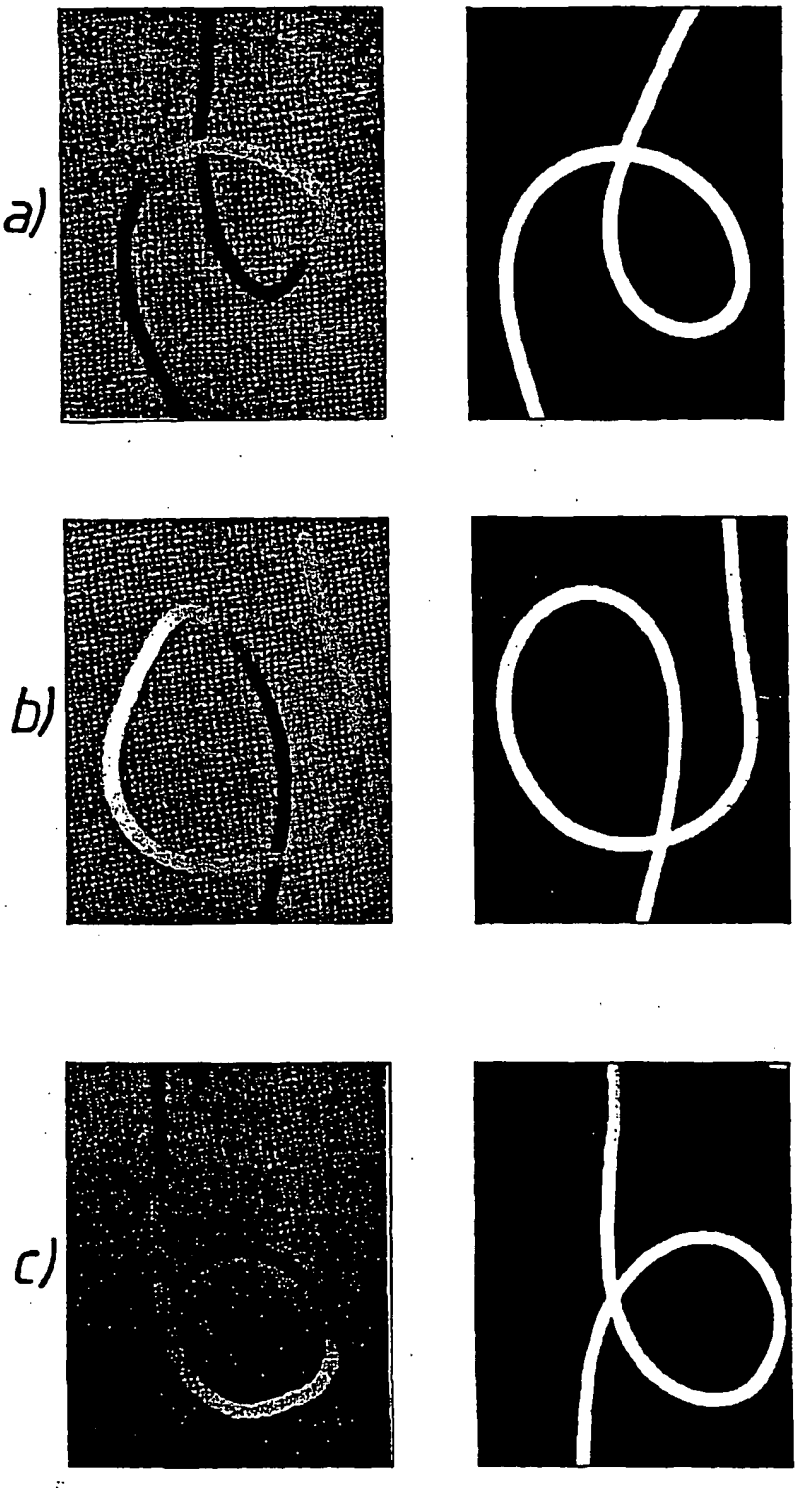
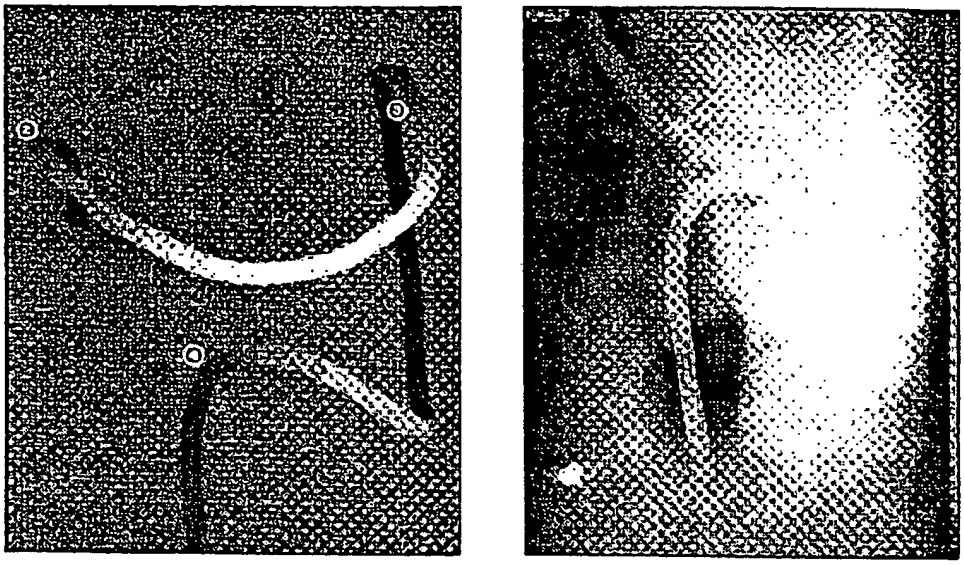


Fig.12

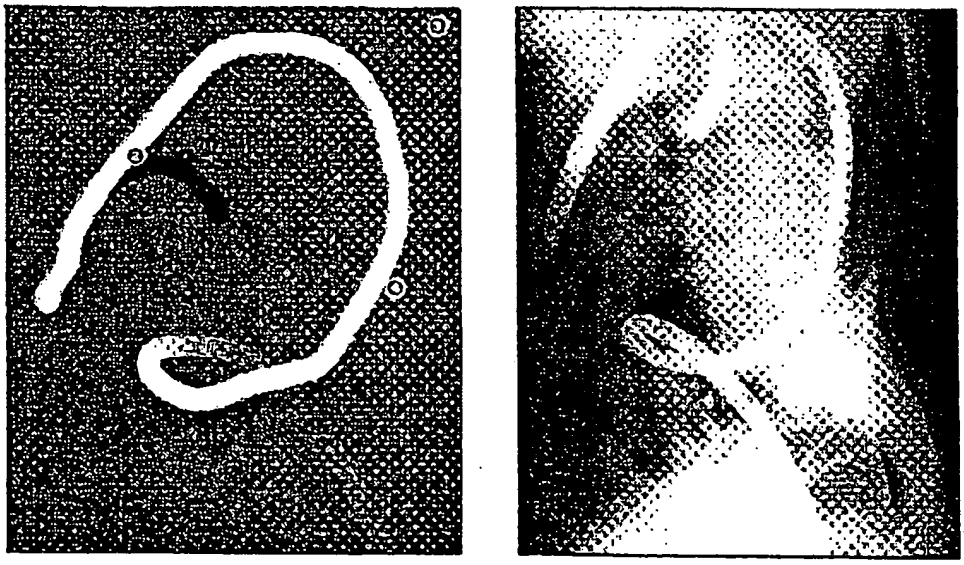
BEST AVAILABLE

Fig. 13

(a)



(b)



BEST AVAILABLE COPY